Current status of neutrino mixing

Justin Evans

FPCP - Israel

24th-28th May 2011

Neutrino disappearance

1970s

Homestake Mine

1970s onwards: Ray Davis looked for neutrinos from the Sun

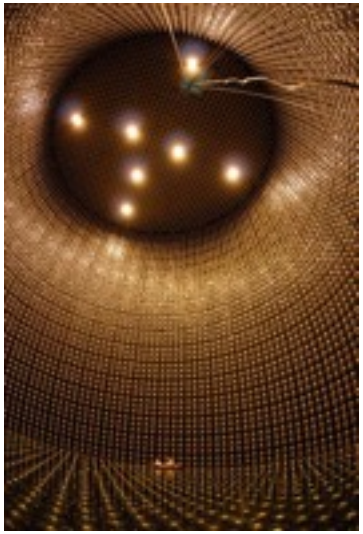
- Saw significantly fewer than predicted by solar models

Neutrino disappearance

1970s

Homestake Mine

1990s



Super-Kamiokande

1990s: Super-Kamiokande observed disappearance of muon neutrinos

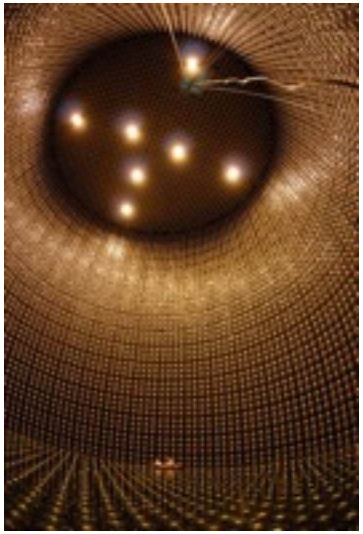
- As a function of L/E

Neutrino disappearance

1970s

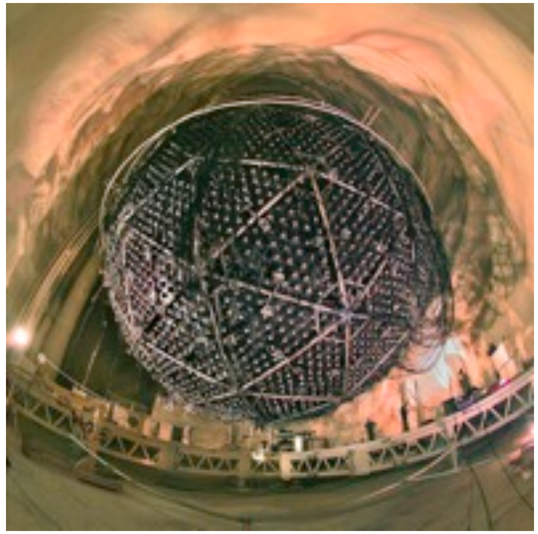
Homestake Mine

1990s



Super-Kamiokande

2000s



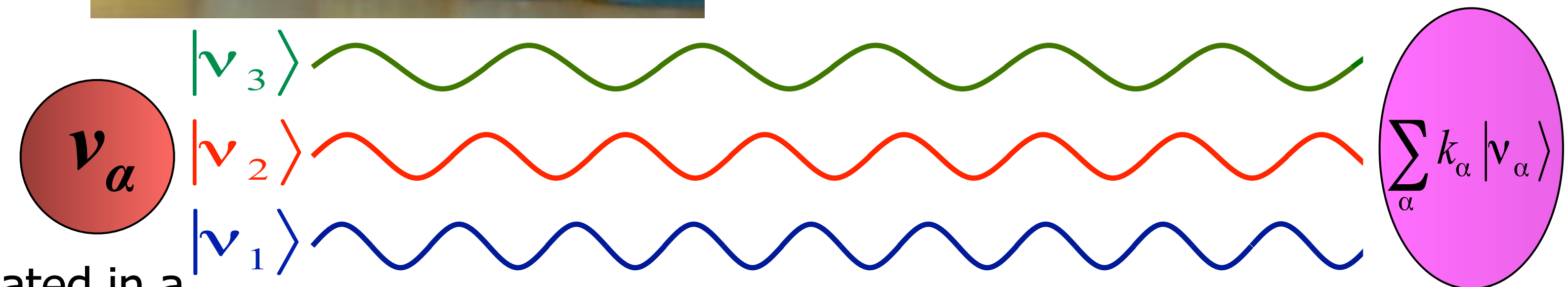
SNO

2000s: SNO sees disappearance of solar electron neutrinos

- No deficit in the neutral current event rate
- Confirms conservation of total neutrino number

Neutrino flavour change – Oscillations

➢ Neutrino flavour states do not correspond to mass states



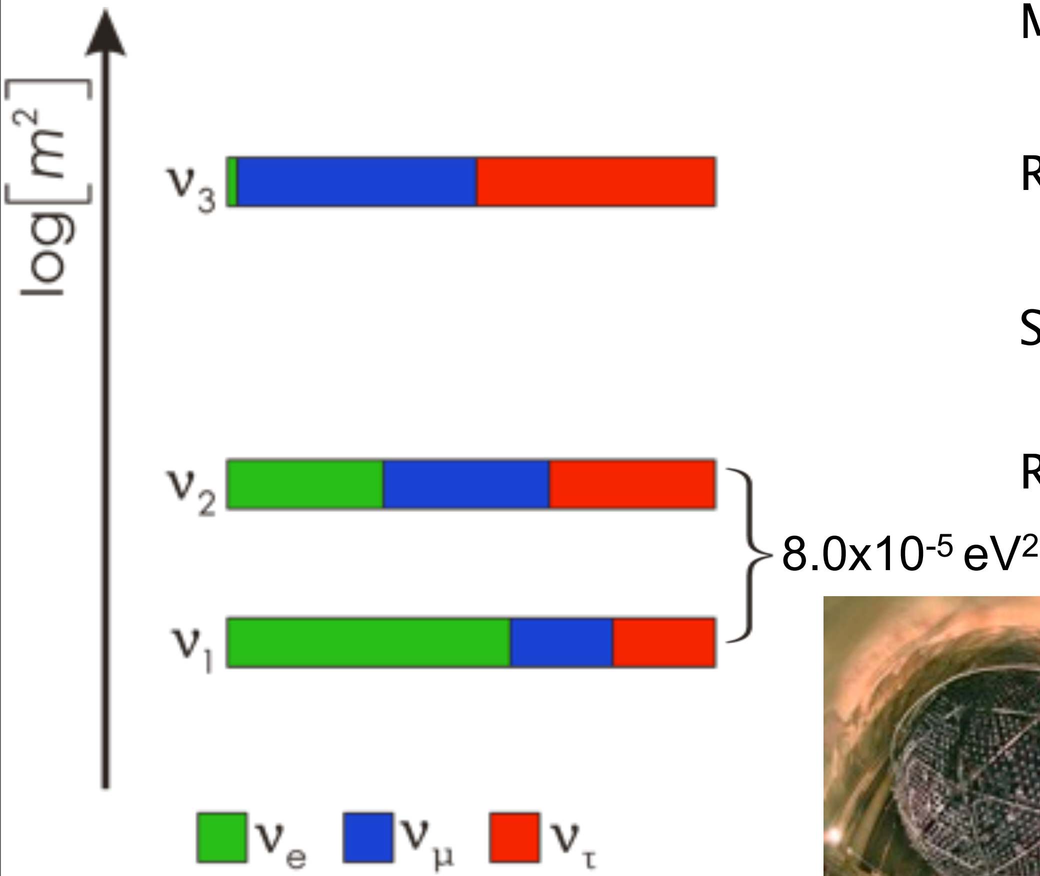
Created in a flavour eigenstate

Propagate as mass eigenstates

On detection, collapse back to flavour state: now not an eigenstate

Quantum mechanical interference on a macroscopic scale

Solar sector



Smallest mass splitting

Mixing angle θ_{12}

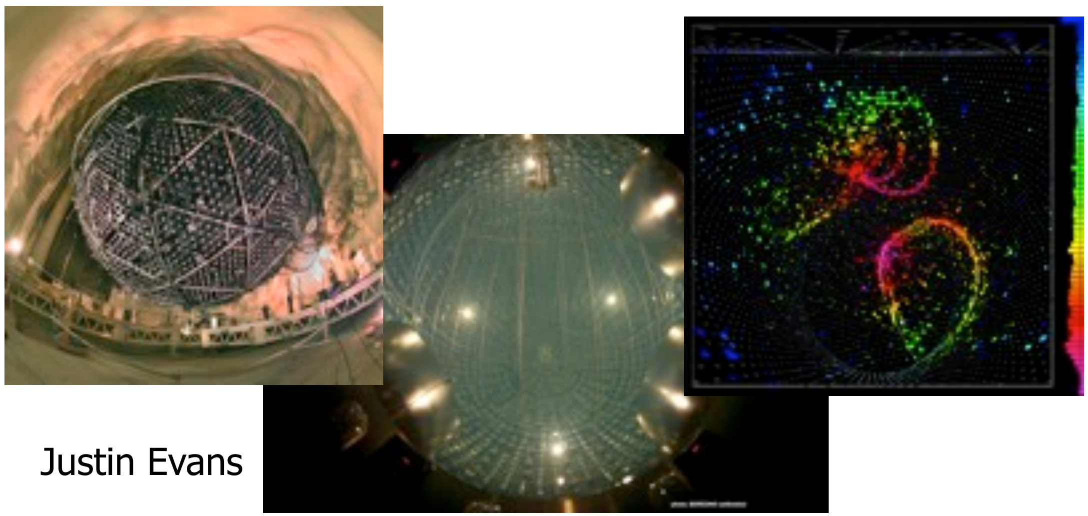
Require L/E ~ $\mathcal{O}$(10^5 km/GeV)

Solar neutrinos

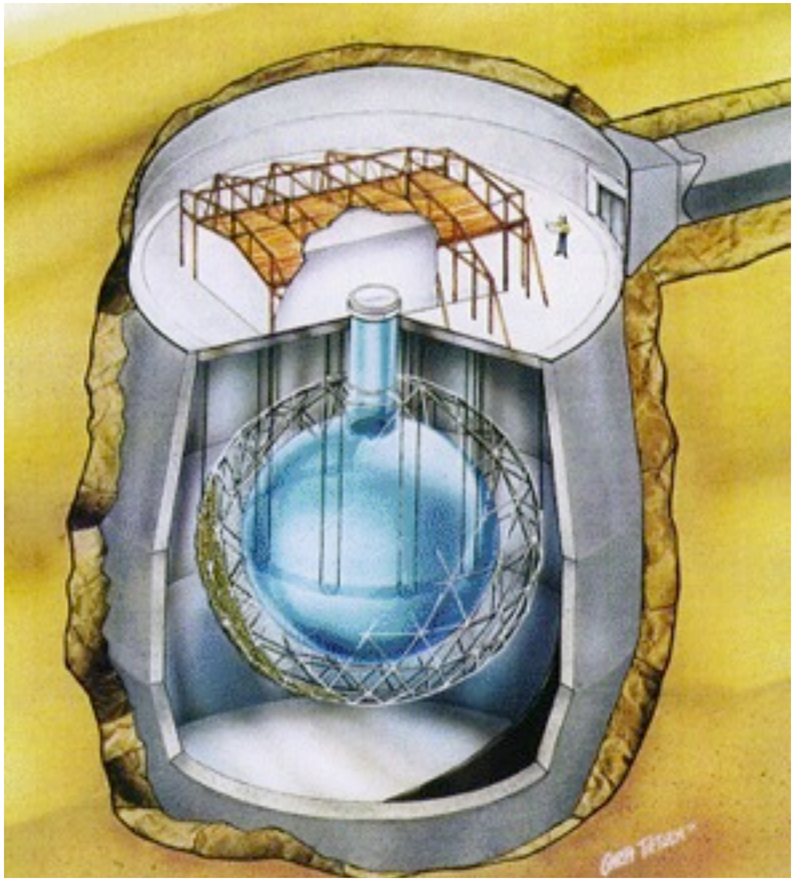
- SNO, Borexino, etc

Reactor neutrinos over $\mathcal{O}$(100 km)

- KamLAND

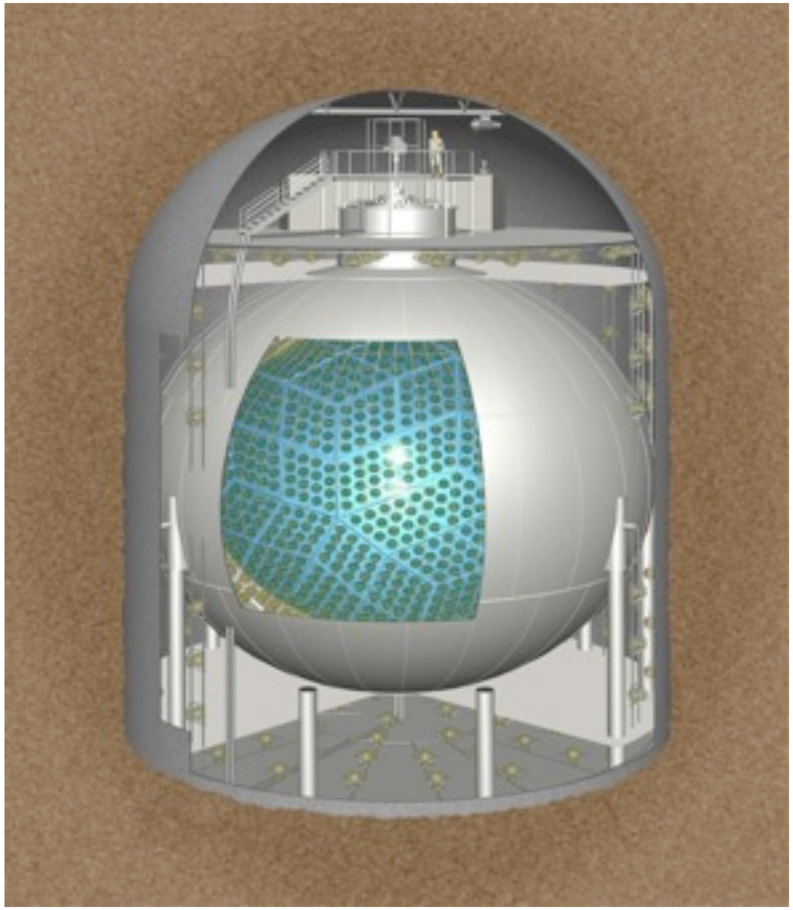


SNO



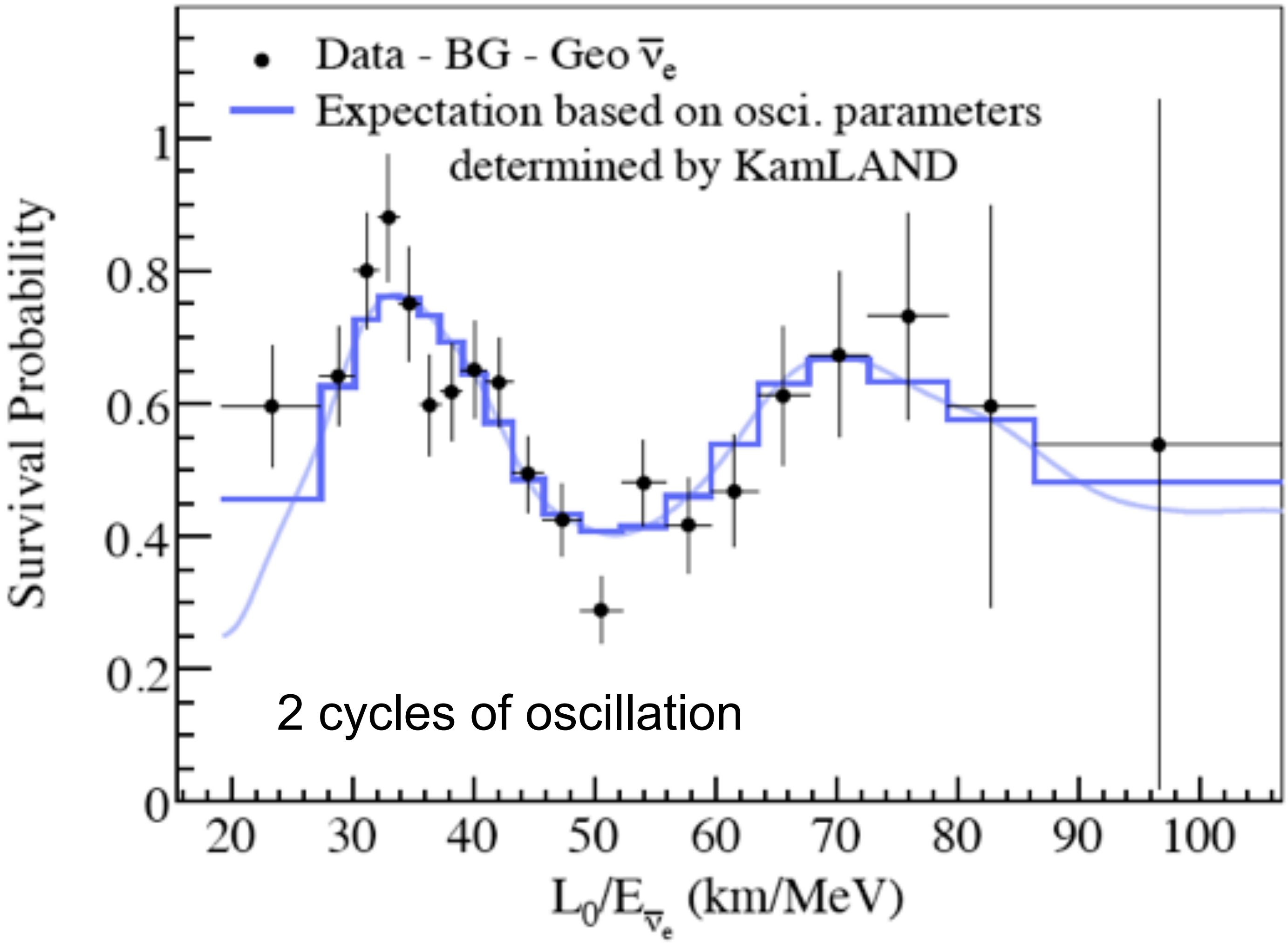
1000 tons of D_2O
2092 m underground
Measure both CC and NC interactions

KAMLand



1 kton liquid scintillator
Surrounded be reactors, typically 180 km away

KamLAND data



Solar sector

SNO low-energy threshold analysis

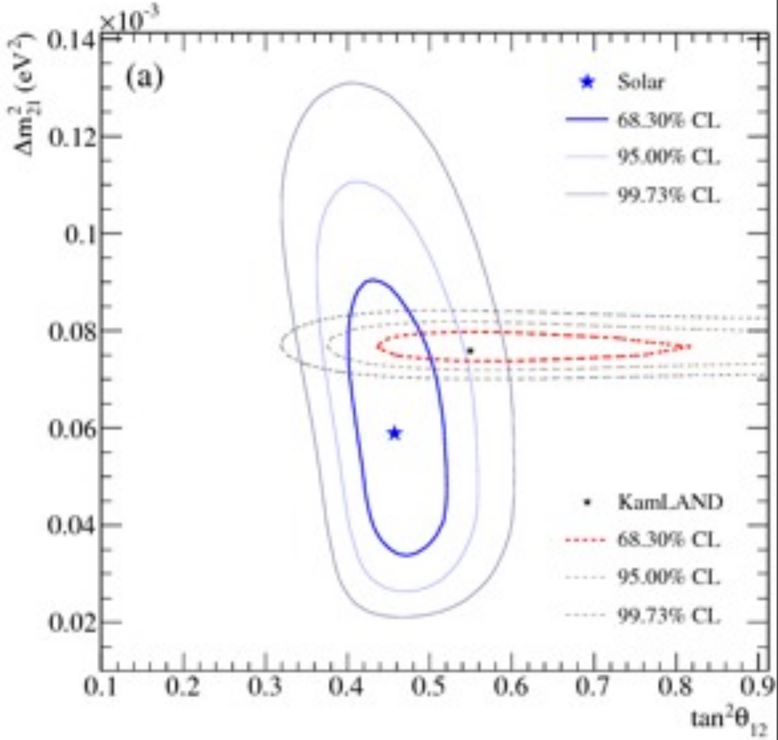
Borexino, gallium and chlorine experiments

KamLAND data

Two-neutrino model:

- $\Delta m^2_{21} = +7.59^{+0.20}_{-0.21} \times 10^{-5}$ eV^2
- $\theta_{12} = 34.06^{+1.16}_{-0.84}$

Solar sector



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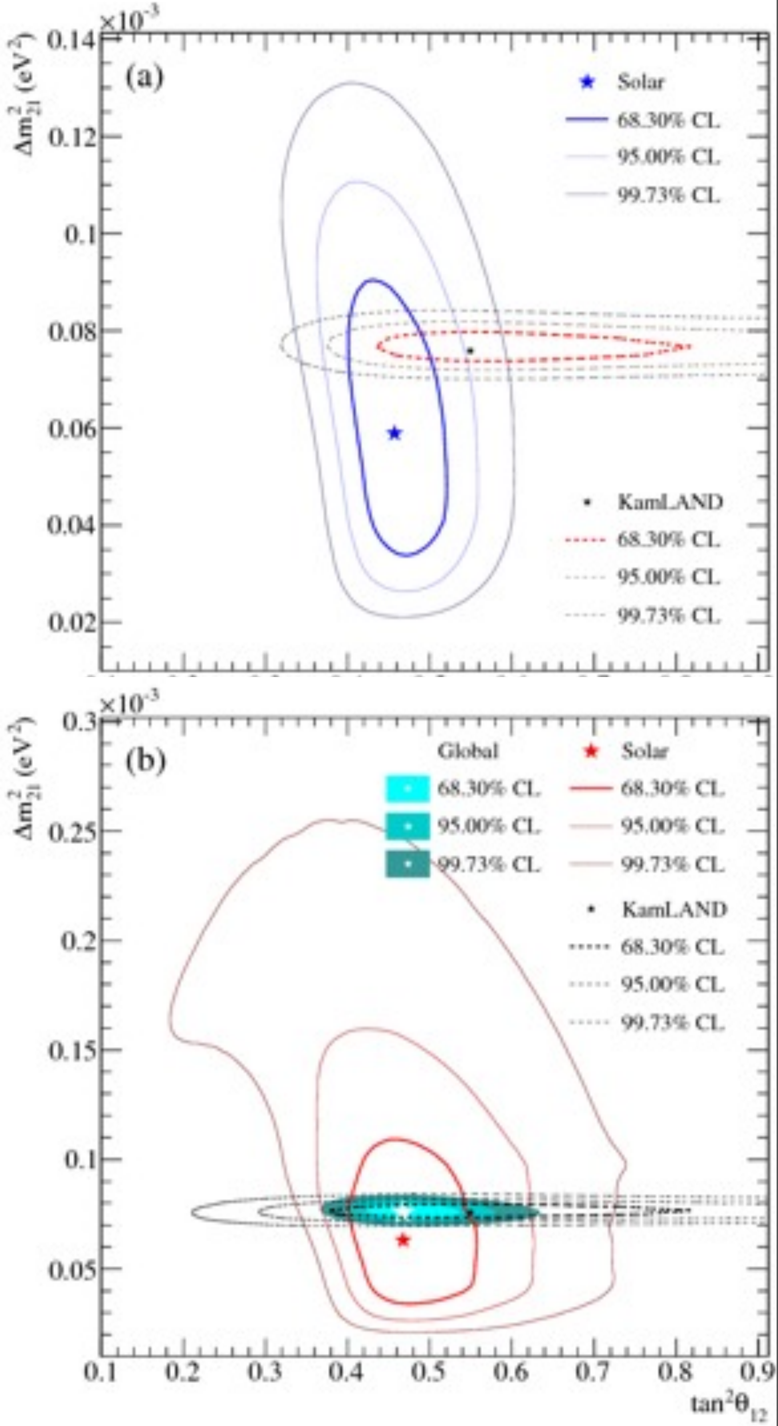
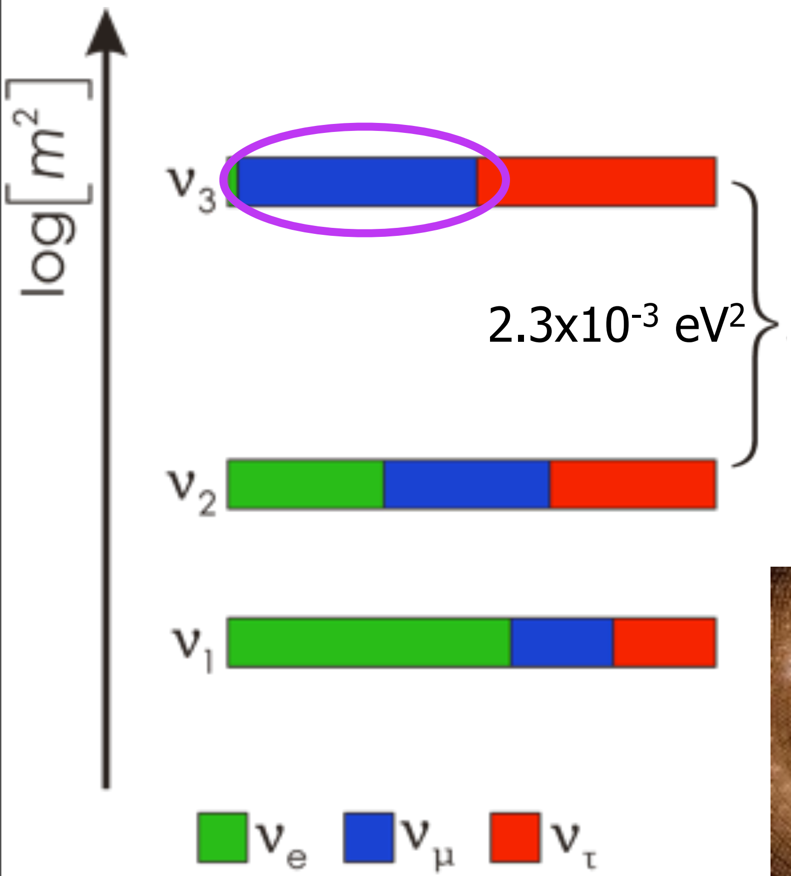


Atmospheric sector



Largest mass splitting

Mixing angle θ_{23}

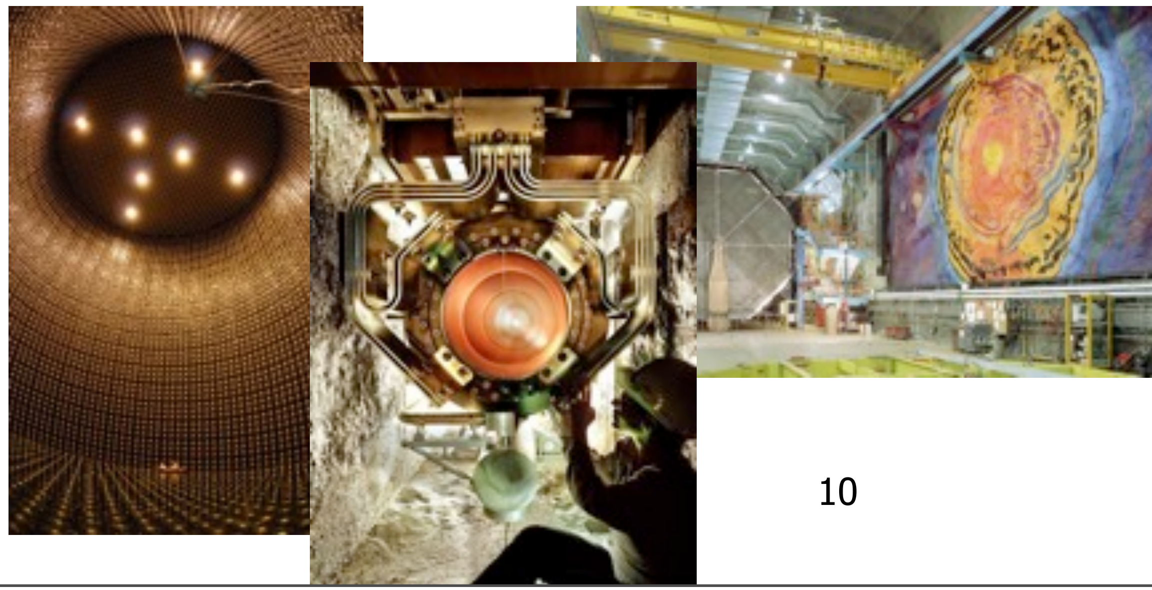
Require L/E ~ $\mathcal{O}(10^3$ km/GeV)

Atmospheric neutrinos

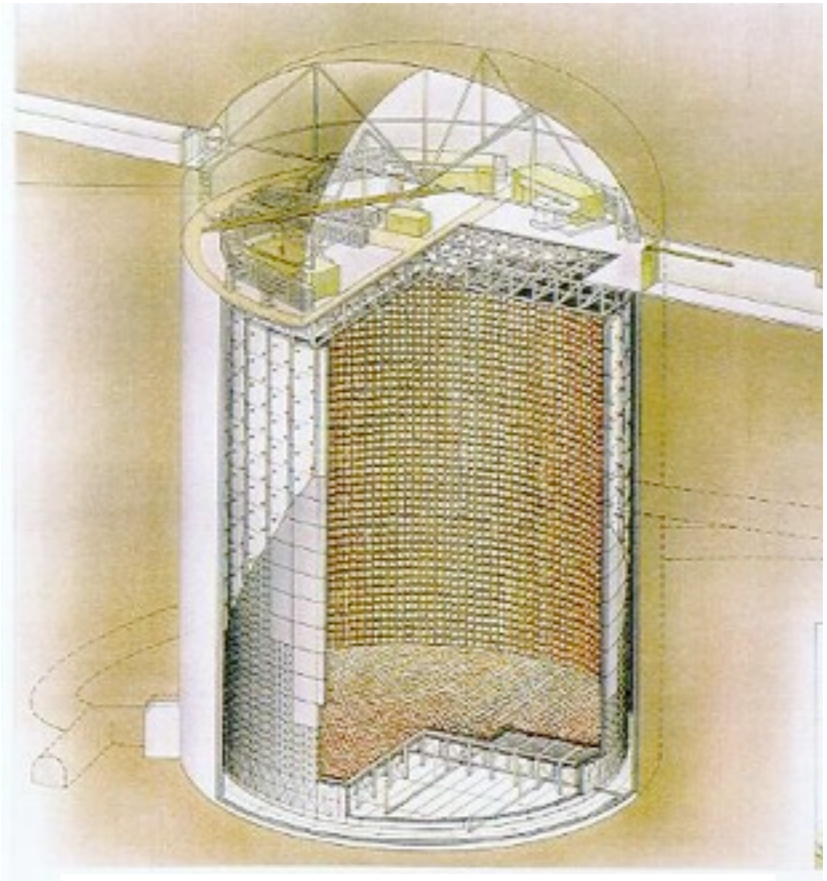
- Super-K, MACRO, Soudan2, etc

Accelerator neutrinos

- MINOS, Nova, T2K, etc



Super-Kamiokande



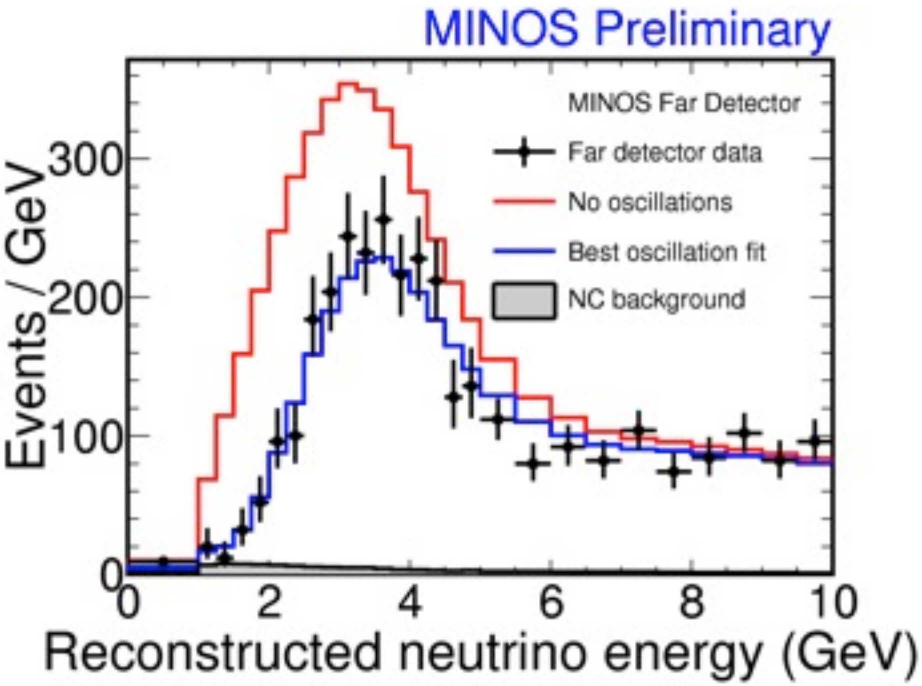
50 kt of water
42m high, 40 m diam
40% PMT coverage
1000m underground

MINOS

Far Detector
5,400 tonnes
Iron-scintillator calorimeter

Near Detector
980 tonnes

MINOS ν_μ disappearance



Use near detector to predict far detector expectation

Expectation with no oscillations

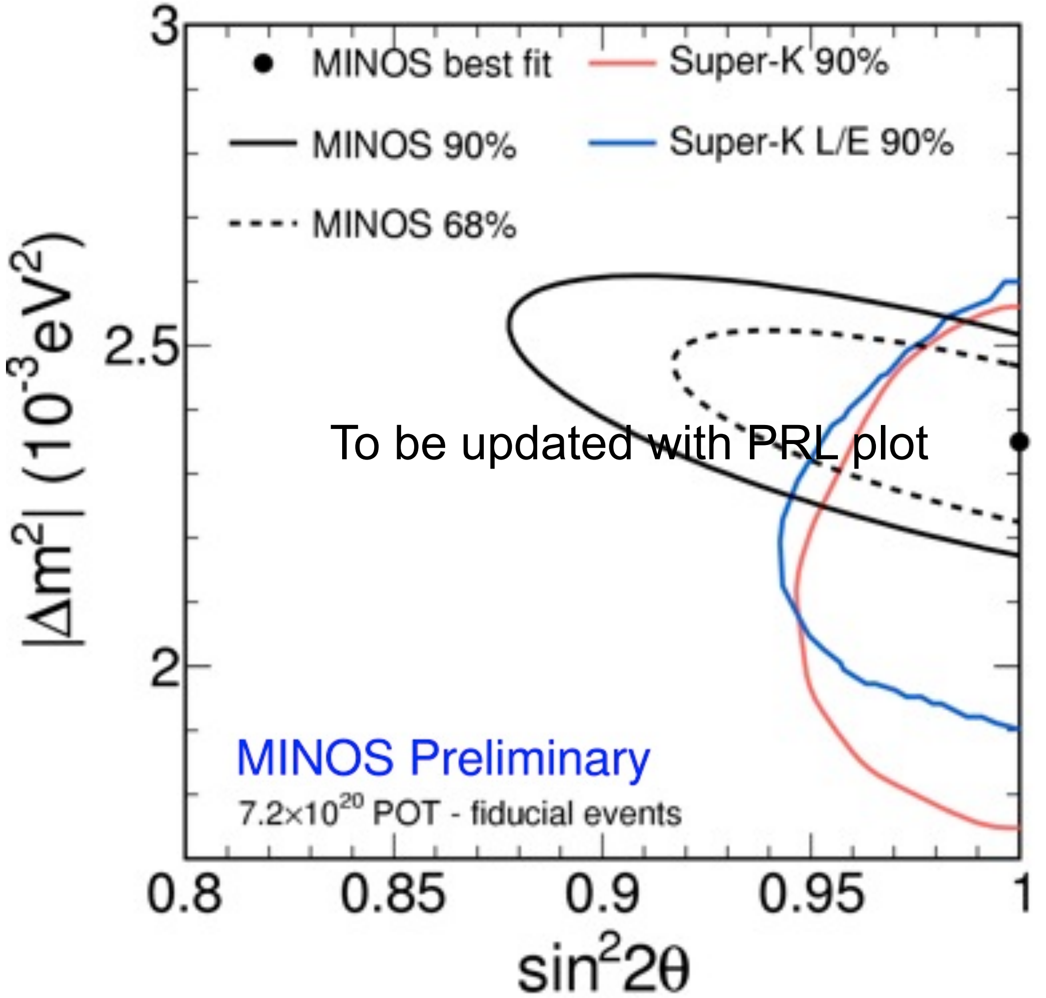
- 2451 events

Observation shows an energy-dependent deficit

- 1986 events

Good fit to the oscillation model

Parameter measurements

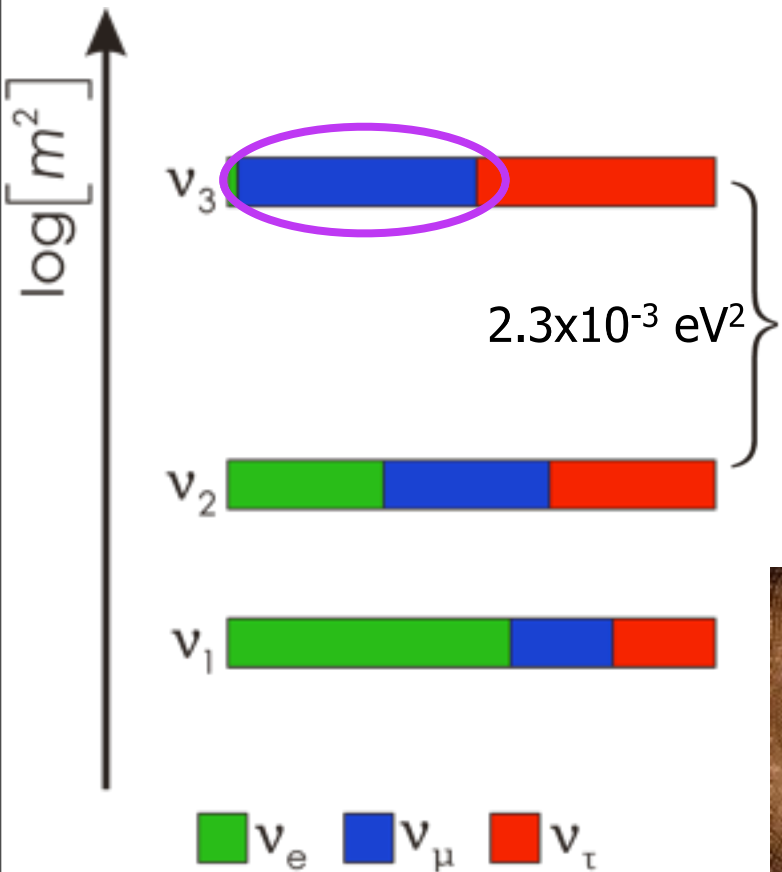


MINOS measurement
Δm_{23}^2**=2.32+0.12/-0.08 x10**$^{-3}$
$\sin^2 2\theta_{23}$**>0.96 (90%C.L.)**

Super-K zenith measurement
Δm_{23}^2**=2.11+0.11/-0.19 x10**$^{-3}$
$\sin^2 2\theta_{23}$**>0.96 (90%C.L.)**

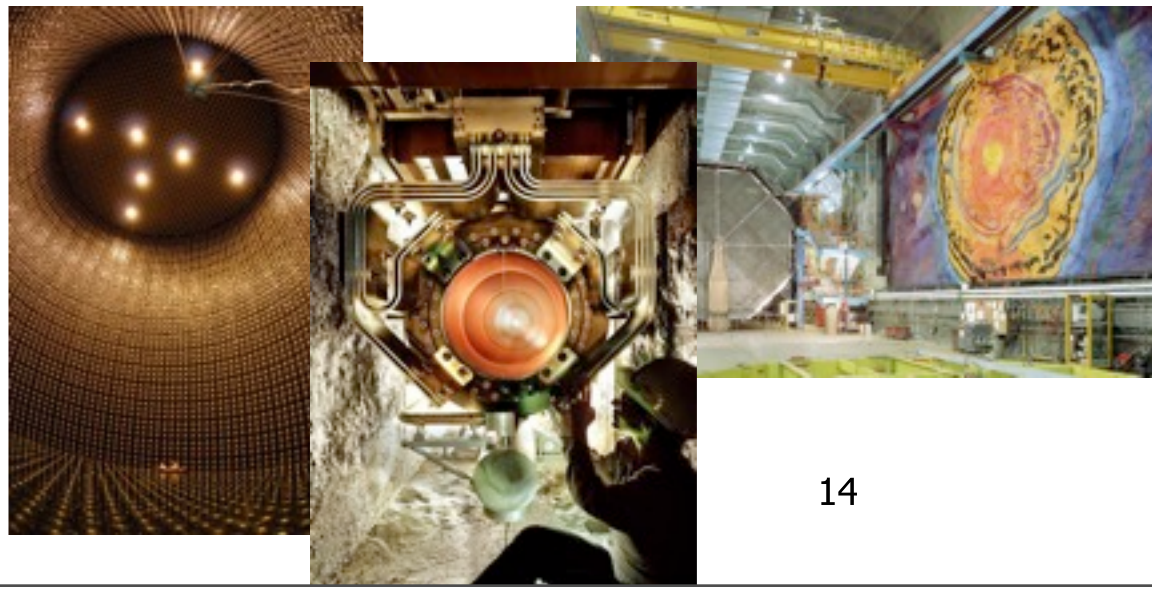
Mixing angle consistent with maximal

Antineutrinos

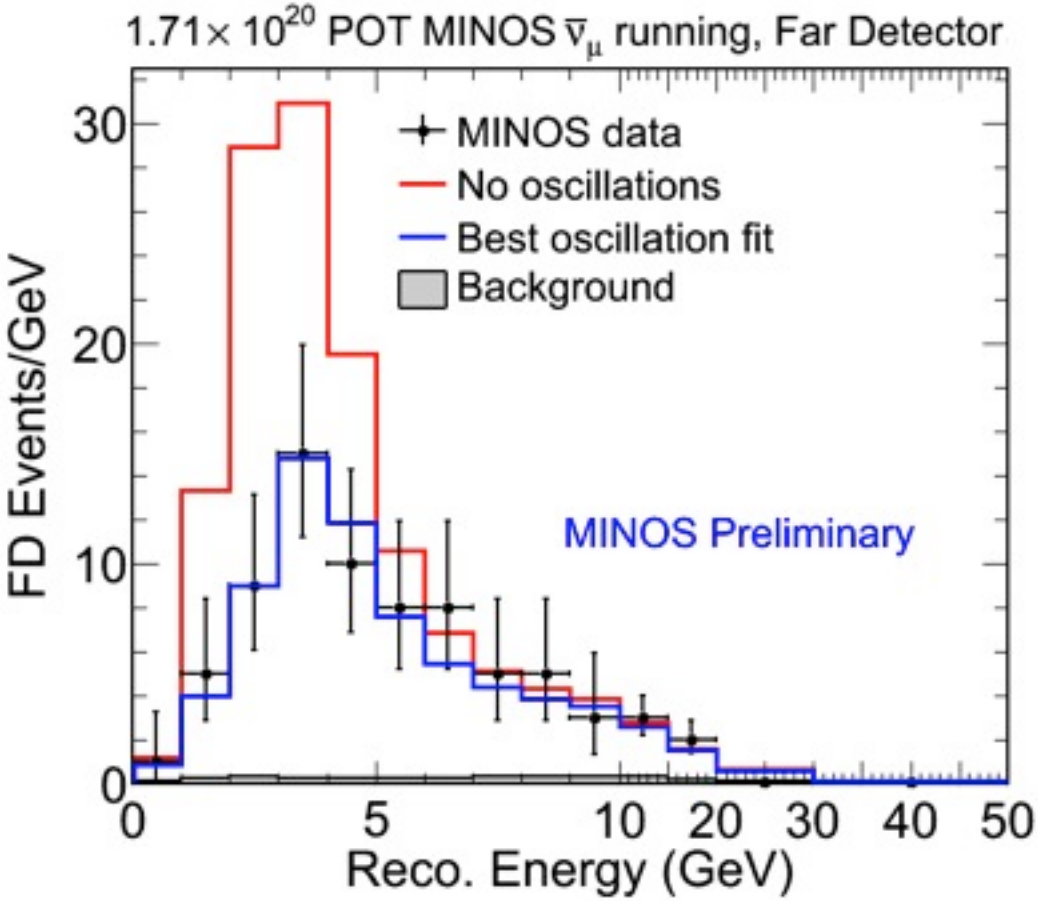


Look at disappearance driven by the larger mass splitting and θ_{23}

Do the same oscillation parameters apply to neutrinos and antineutrinos?



MINOS $\overline{\nu}_\mu$ results

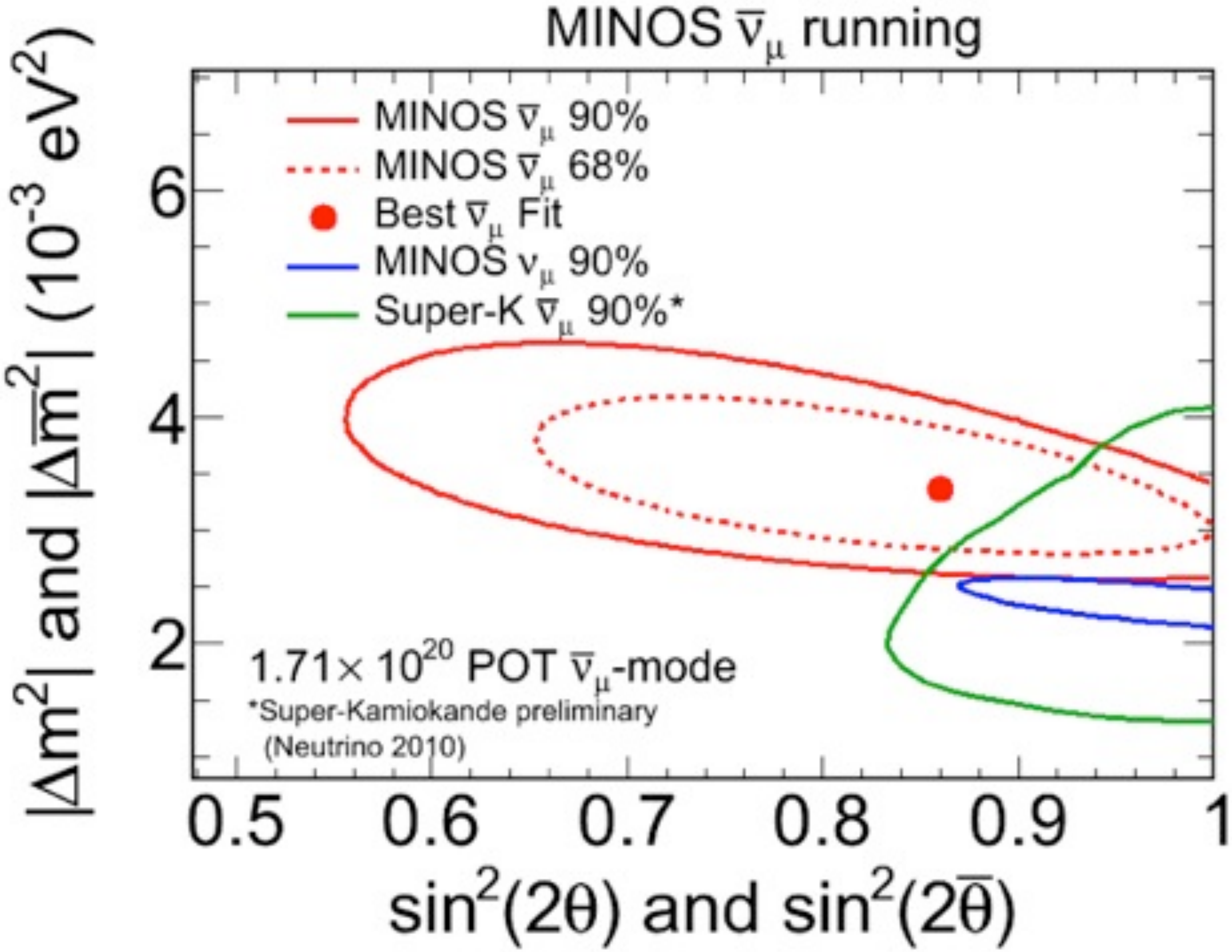


MINOS can perform event-by-event antineutrino identification

At the far detector

- No oscillation prediction: **155 events**
- Observe: **97 events**
- No oscillations disfavoured at 6.3σ

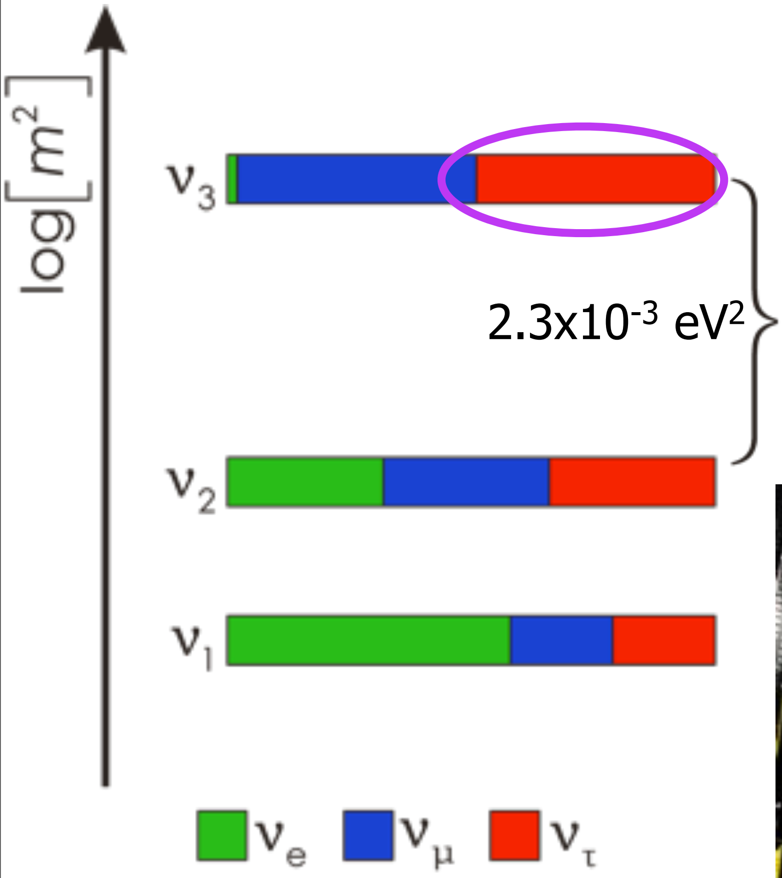
$\bar{\nu}_\mu$ oscillation parameters



MINOS measurement
$\Delta m_{23}^2 = 3.36^{+0.46}_{-0.40}(\text{stat}) \pm 0.06(\text{syst}) \times 10^{-3}$
$\sin^2 2\theta_{23}$ = 0.86+0.11-0.12 (stat)±0.01(syst)

MINOS neutrino and antineutrino parameters are consistent at the 2% C.L.

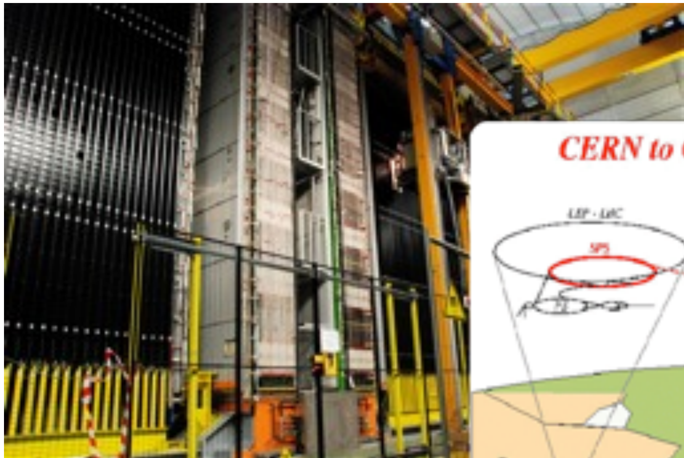
ν_τ appearance



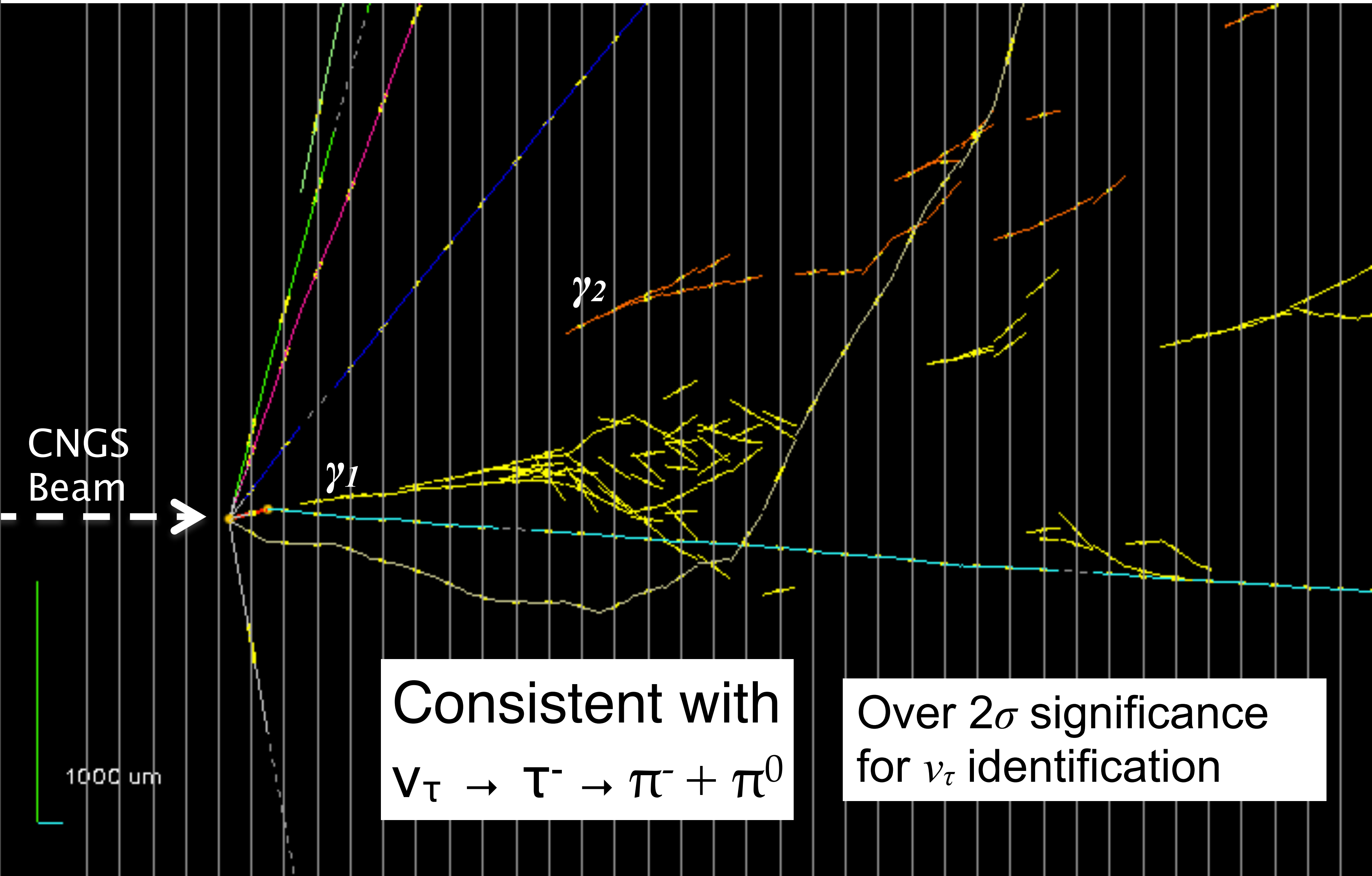
We've seen the muon neutrino disappearance

We think they're turning predominantly into tau neutrinos

Can we observe this tau neutrino appearance?



Opera's first tau neutrino

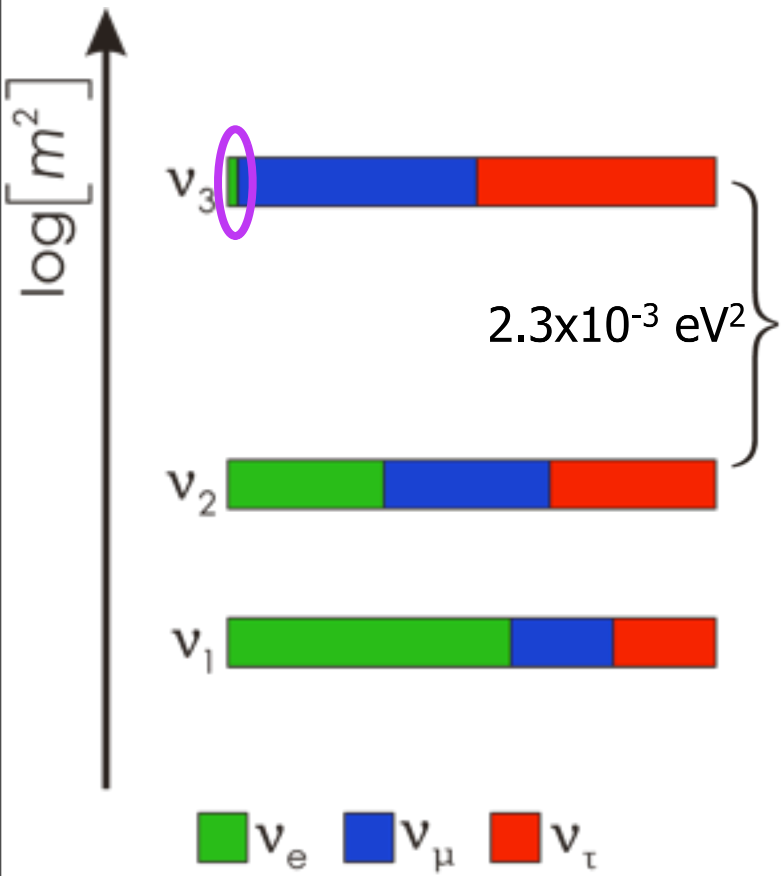


Consistent with

$\nu_\tau \rightarrow \tau^- \rightarrow \pi^- + \pi^0$

Over 2σ significance for ν_τ identification

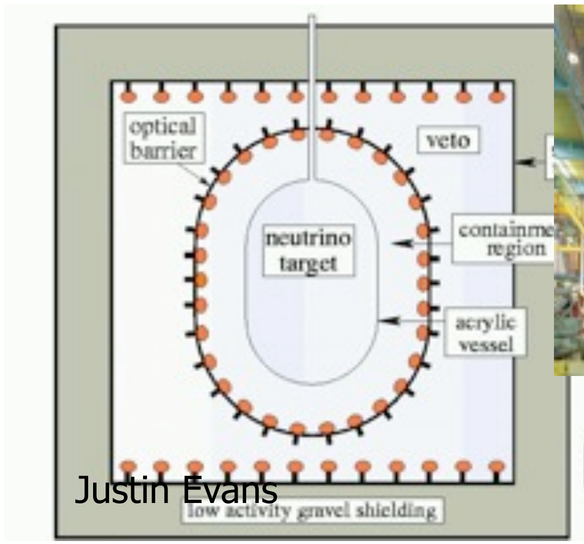
θ_{13}



One mixing angle is yet to be measured

If non-zero, it would cause a small ν_e involvement in oscillations driven by the largest mass splitting

CP violation in the neutrino sector can only be observed if θ_{13} is non-zero



MINOS results

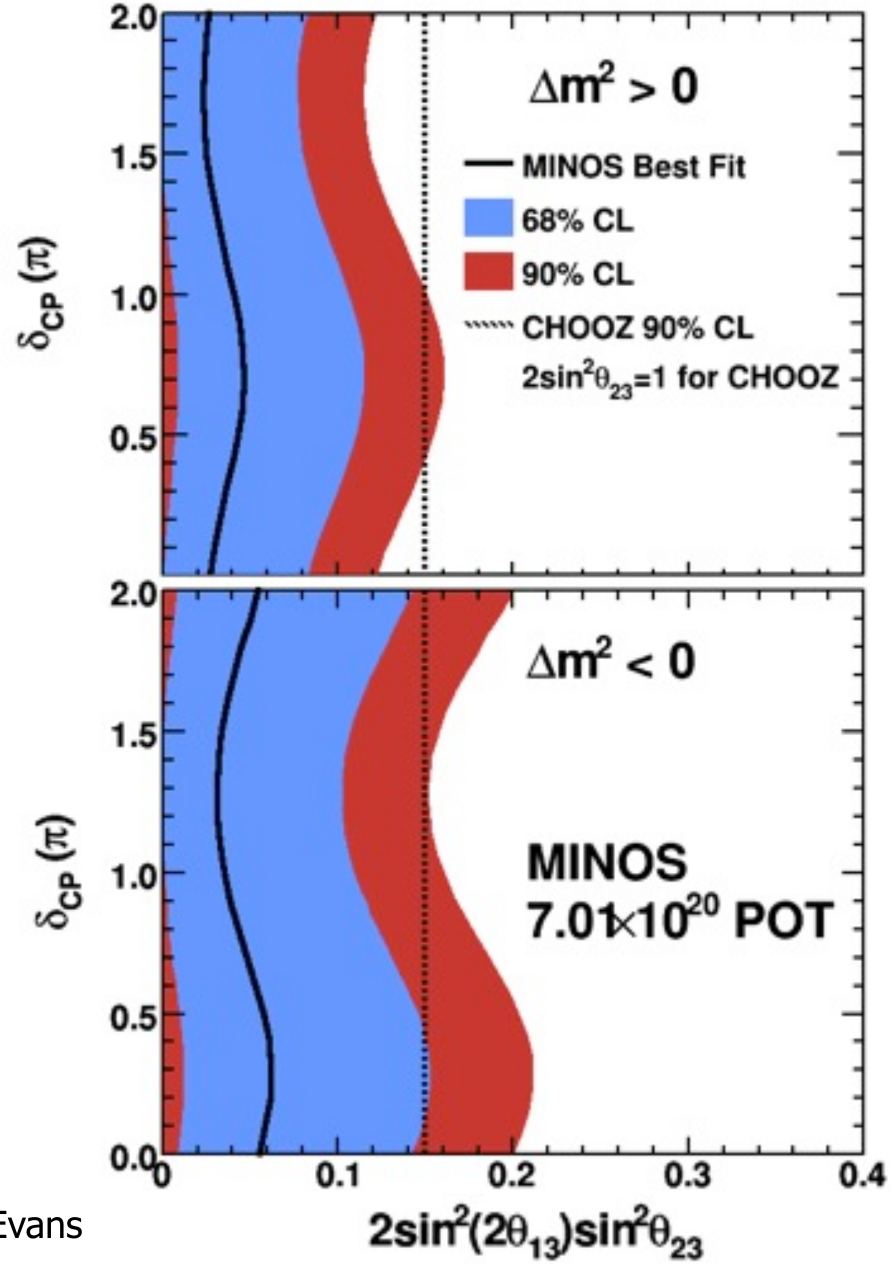
for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1,$

$|\Delta m^2_{32}| = 2.43 \times 10^{-3}\ \mathrm{eV}^2$

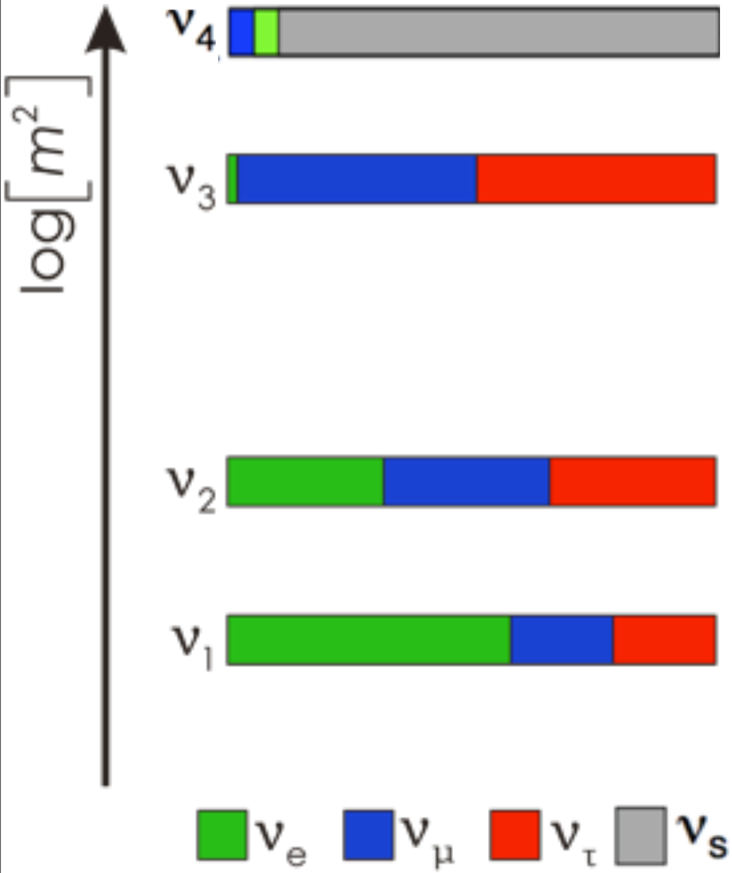
$\sin^2(2\theta_{13}) < 0.12$ normal hierarchy

$\sin^2(2\theta_{13}) < 0.20$ inverted hierarchy

at 90% C.L.



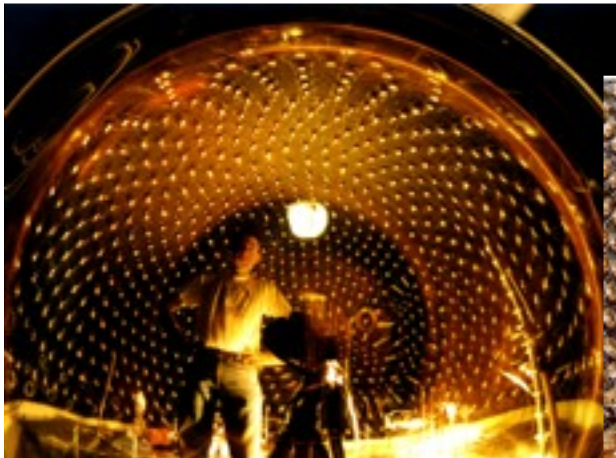
Sterile neutrinos

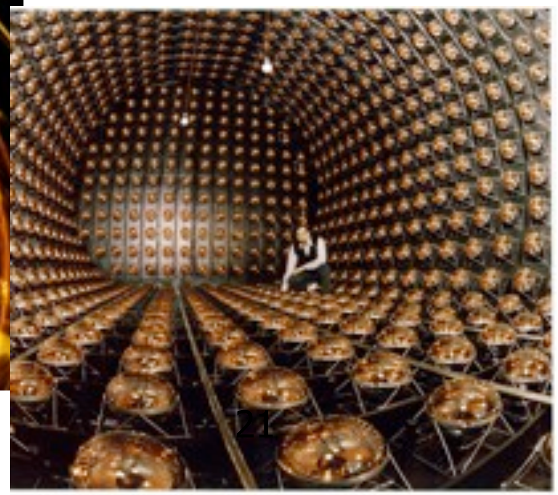


Is there a fourth (or more) sterile neutrino state?

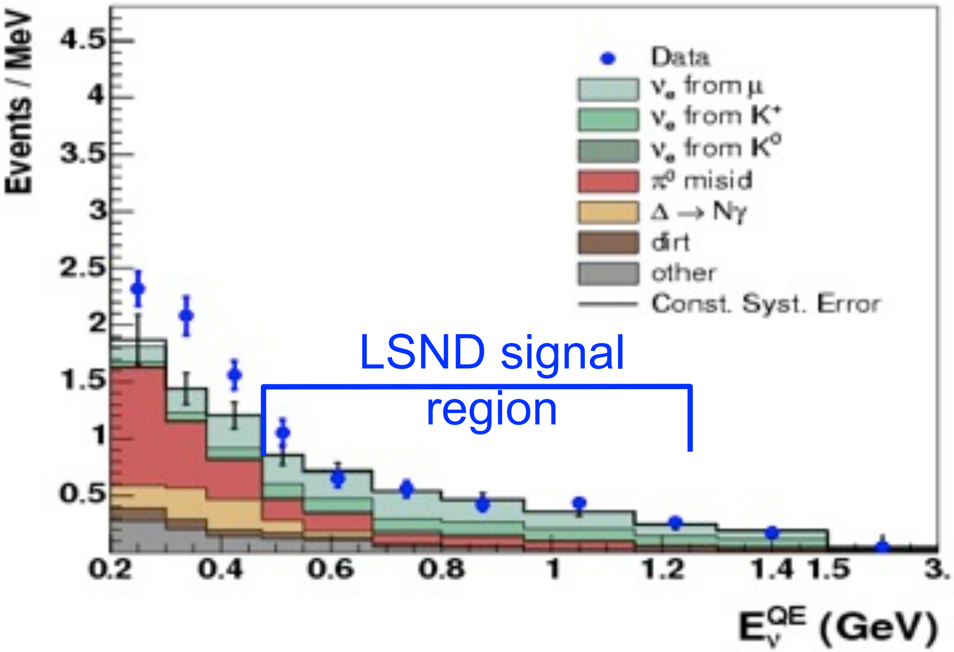
MiniBooNE and LSND work at $L/E \sim \mathcal{O}(1\ \mathrm{km/GeV})$

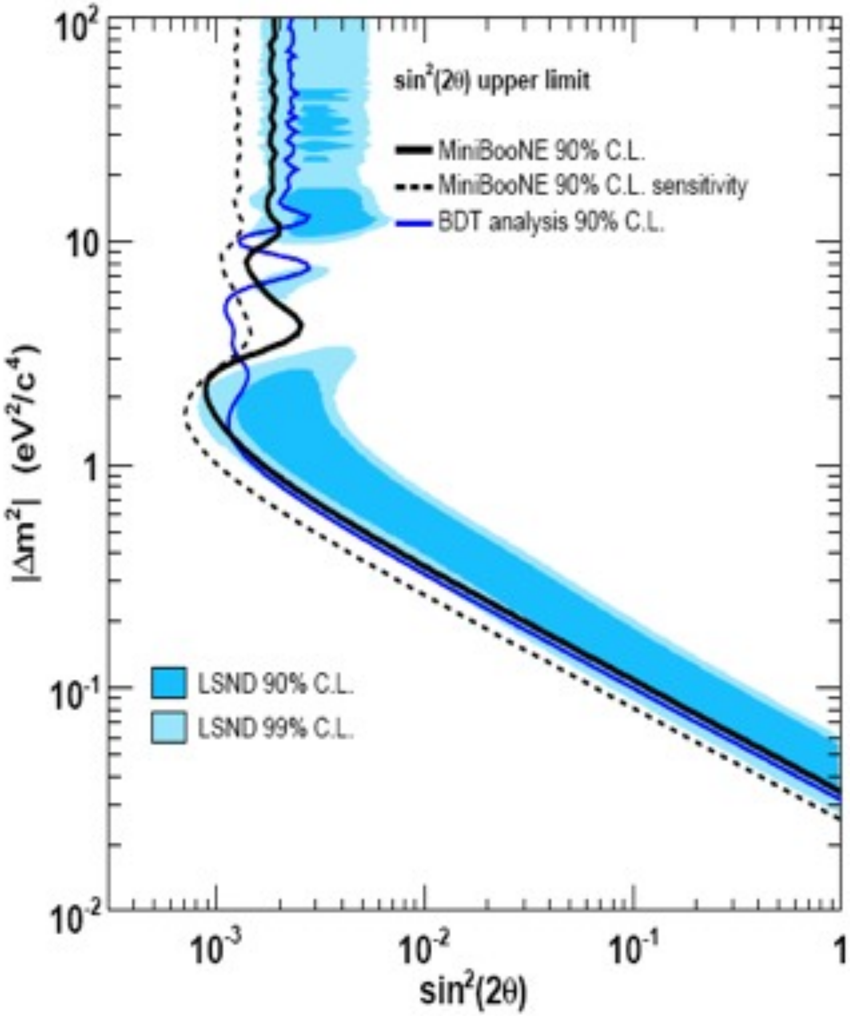
Oscillations would be driven by $\Delta m^2 \sim \mathcal{O}(1\ \mathrm{eV}^2)$





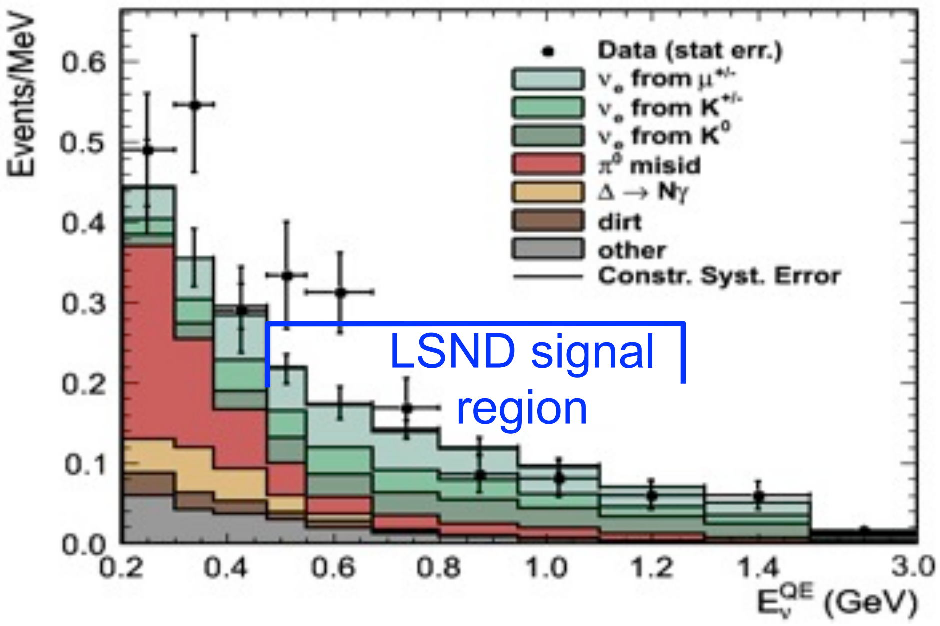
MiniBooNE neutrinos

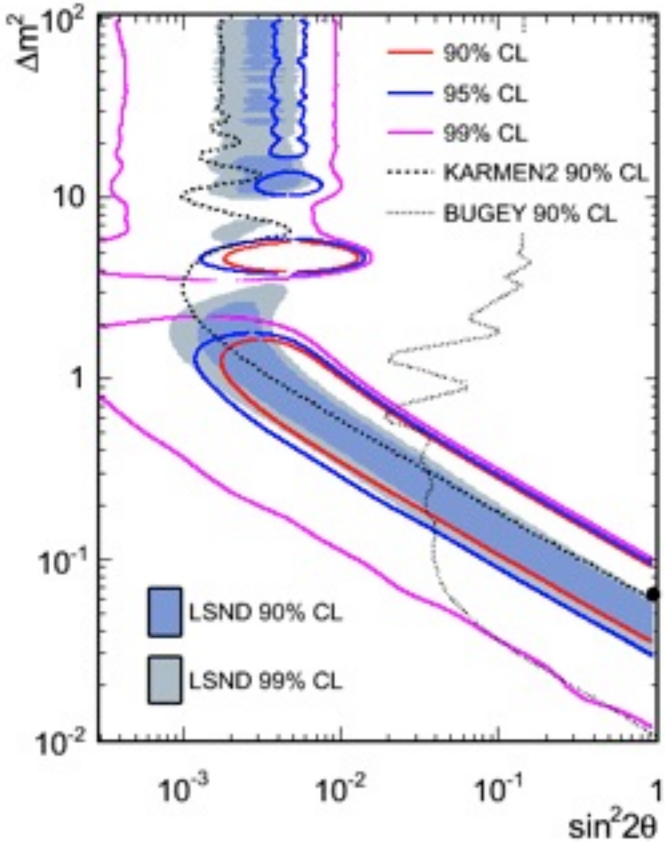




- E < 475 MeV excess has 3σ significance
- Not consistent with the LSND signal assuming a four-neutrino picture

MiniBooNE antineutrinos



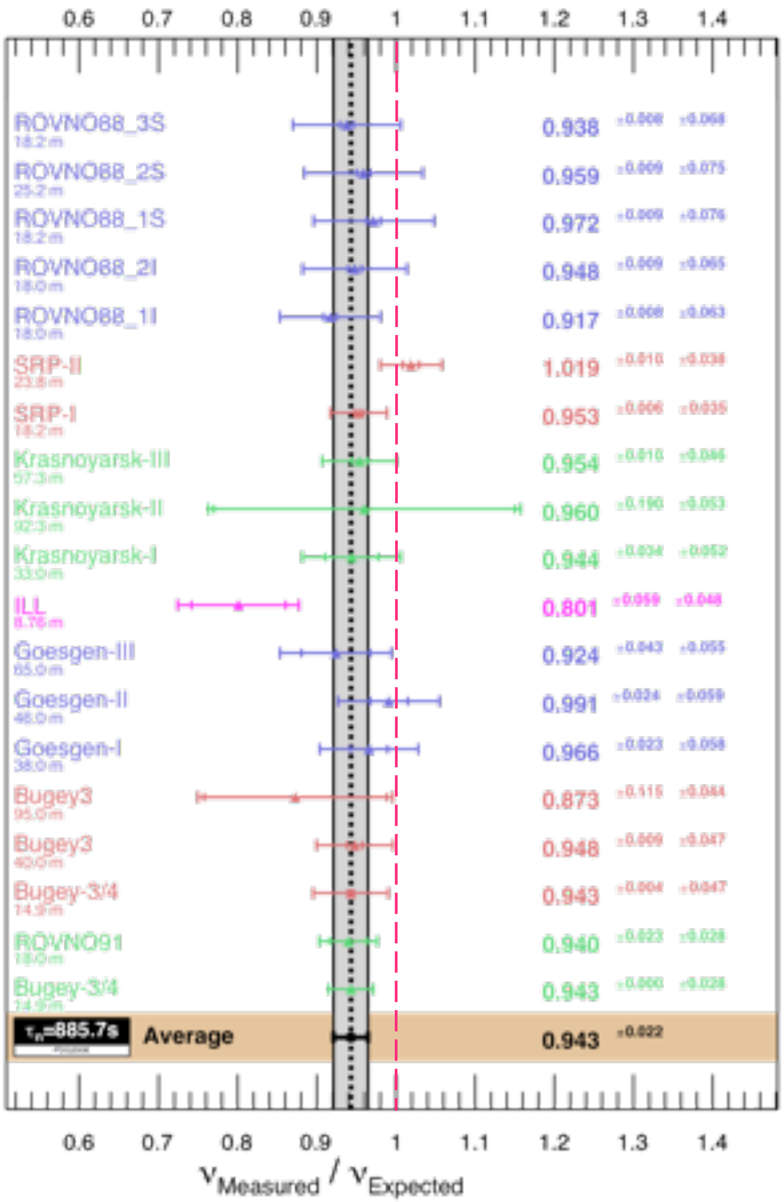


- In the E > 475 MeV region, 0.5% probability for background-only hypothesis

Consistent with LSND oscillation interpretation

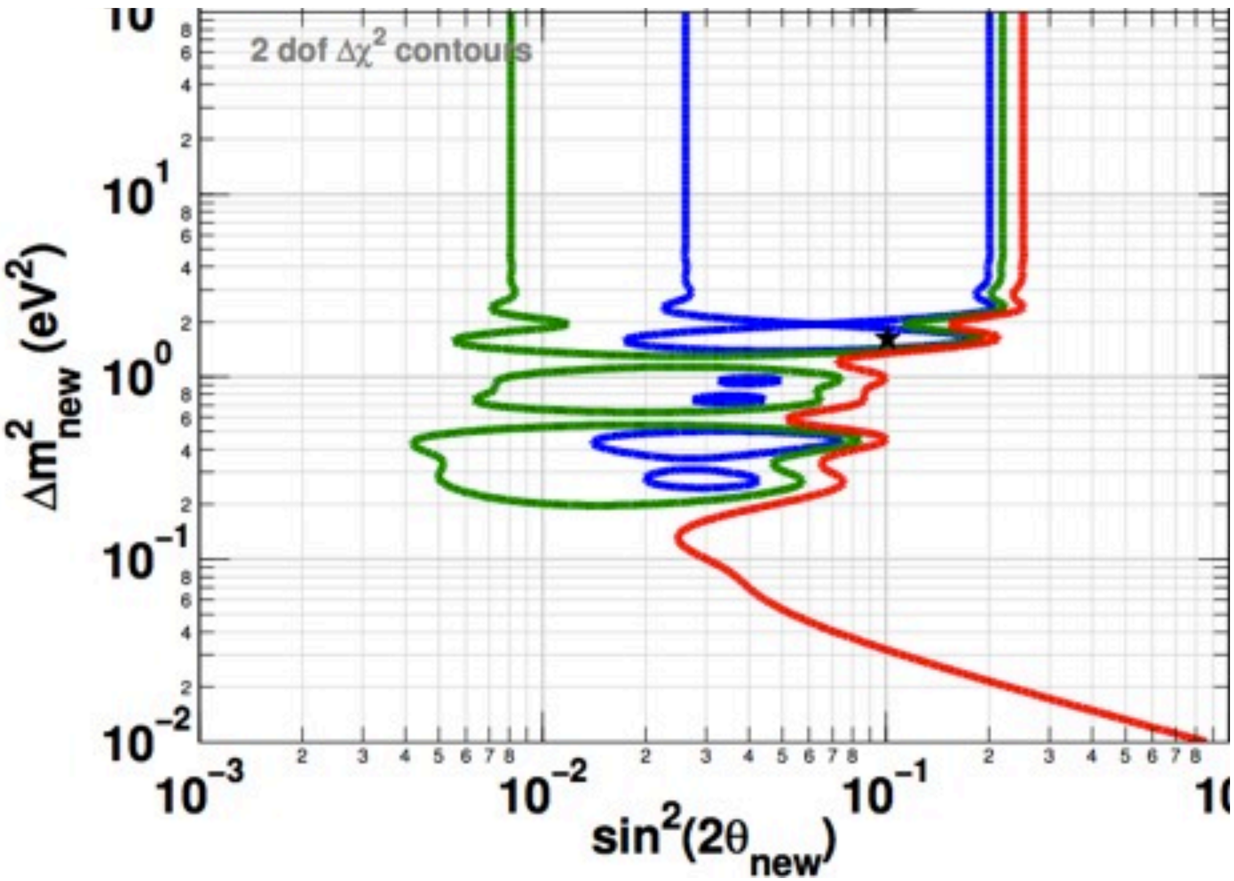
Null hypothesis excluded at 99.4%

Reactor neutrino flux



- Re-evaluation of neutrino flux from nuclear reactors
- Increases the expected flux
- Short-baseline reactor experiments see a 5.7% deficit
- 98.6% significance

Oscillation interpretation



Best fit: $\sin^2 2\theta \sim 0.1$, $\Delta m^2 \sim 1.5$ eV^2

No oscillation disfavoured at 96.51%

Summary

At 3σ we have measured

- Δm^2_{solar} to 2.5%, $\sin^2\theta_{12}$ to 6%
- $\Delta m^2_{atmospheric}$ to 5%, $\sin^2\theta_{23}$ to 11%

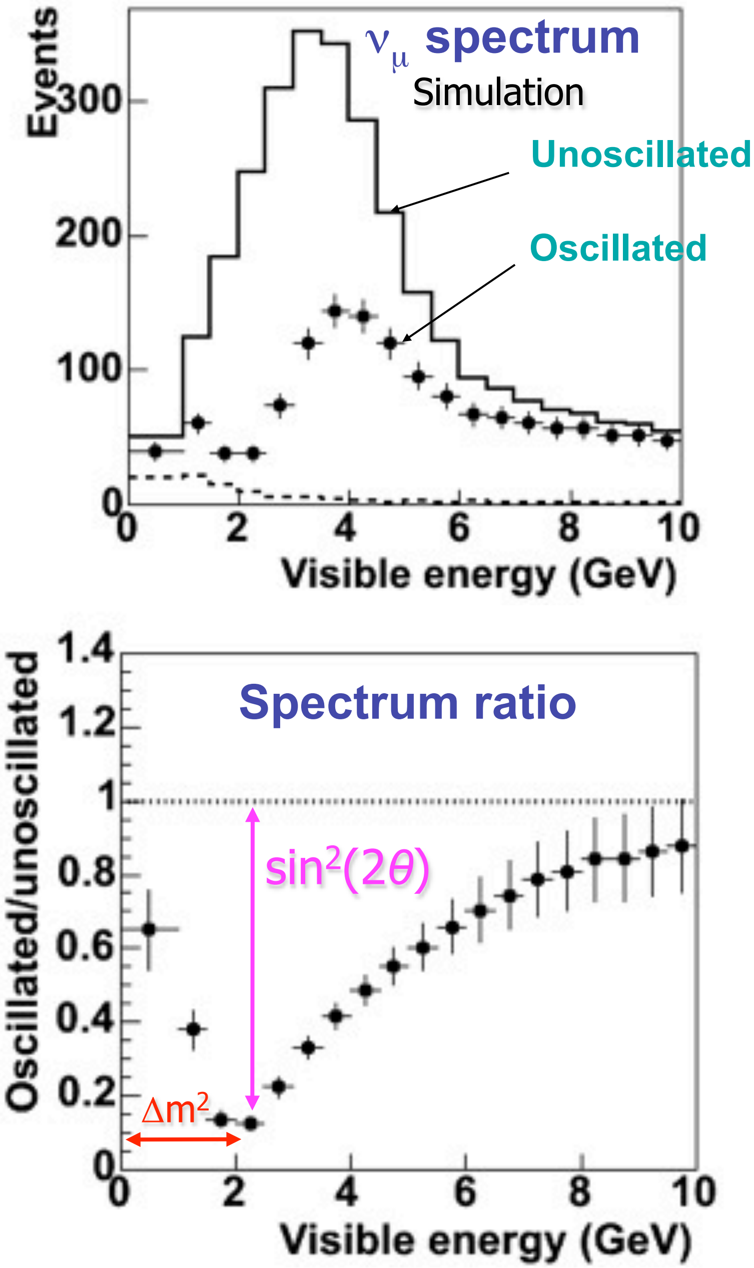
We know the sign of Δm^2_{solar}

We know $\sin^2\theta_{13} < \sim 0.2$ (90% C.L.)

What we don't know

- The value of θ_{13}
- The sign of $\Delta m^2_{atmospheric}$
- Is θ_{23} maximal?
- How much CP violation is there in the neutrino sector?
- Are there sterile neutrinos?
- Do neutrinos and antineutrinos have the same oscillation parameters?

Backup slides



Observing oscillations

Difference between mass states

Amount of flavour-mass mixing

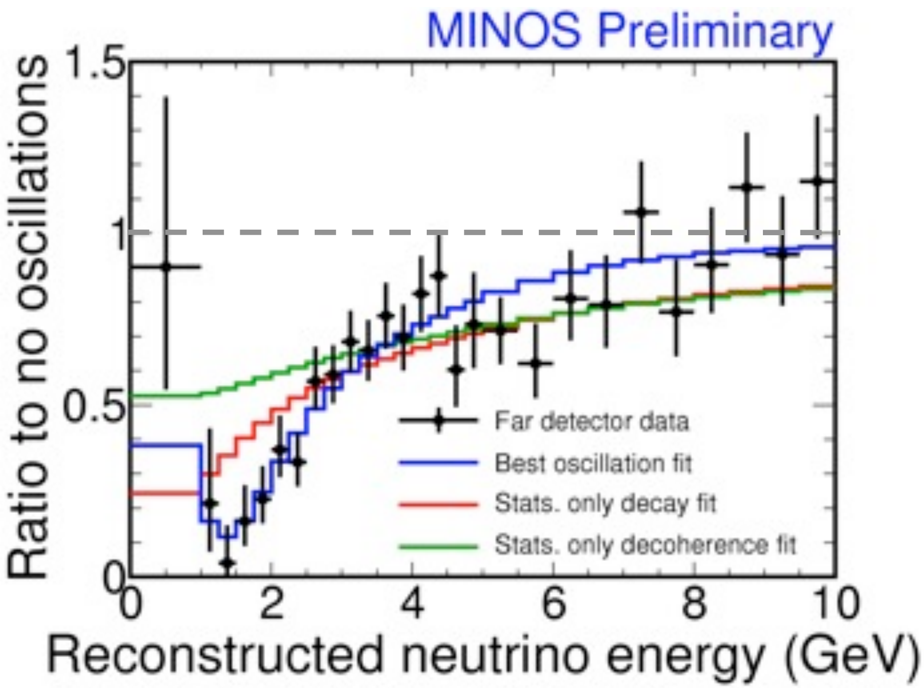
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{E}\right)$$

To observe maximum disappearance:

$$\frac{\Delta m^2 L}{E} = O(1)$$

Δm^2 : eV^2 L : km E : GeV

Are oscillations the best model?



Look at the ratio of our data to the expectation with no disappearance

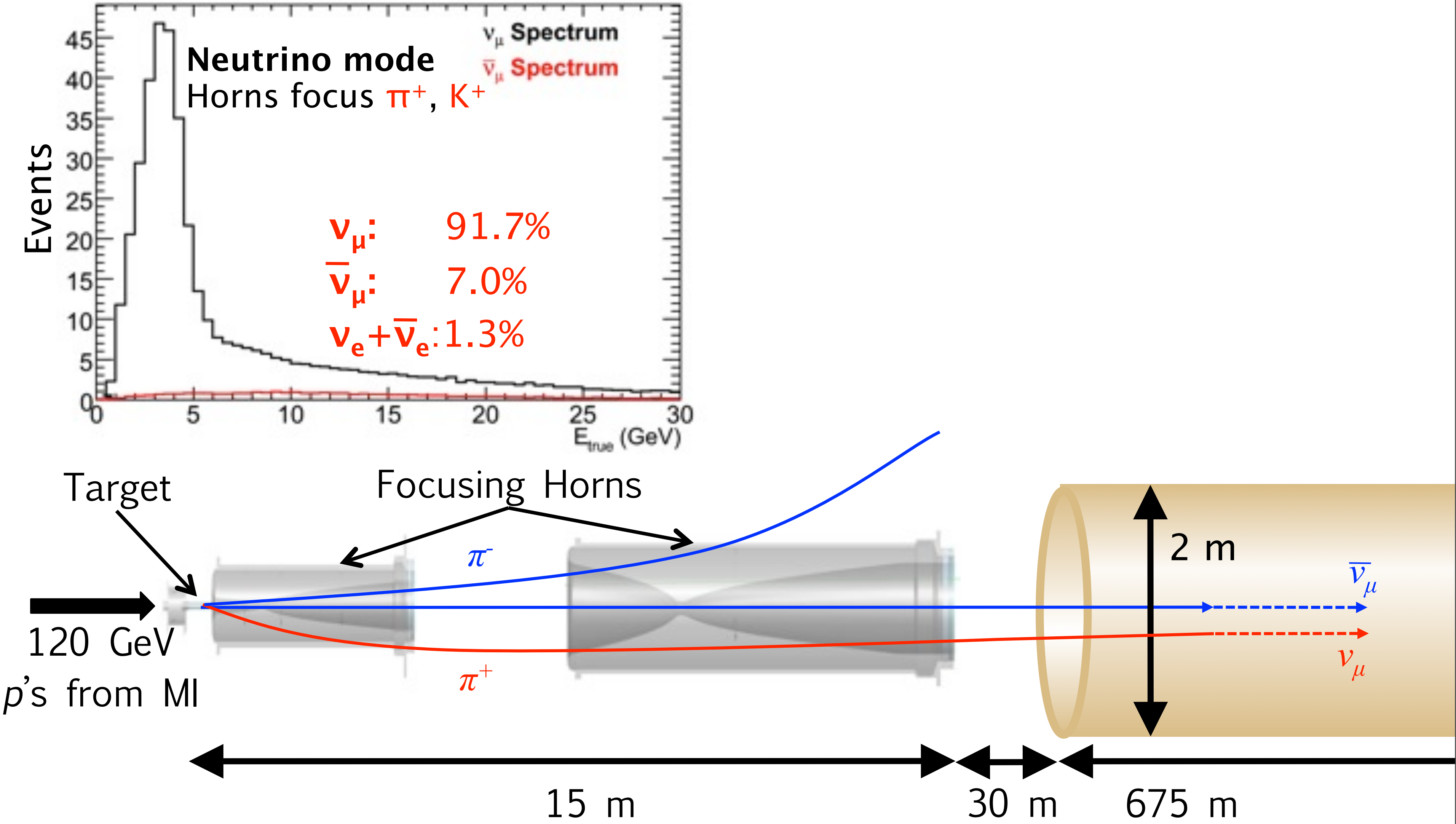
Oscillations fit the data well

Pure decay† disfavoured at **6σ**

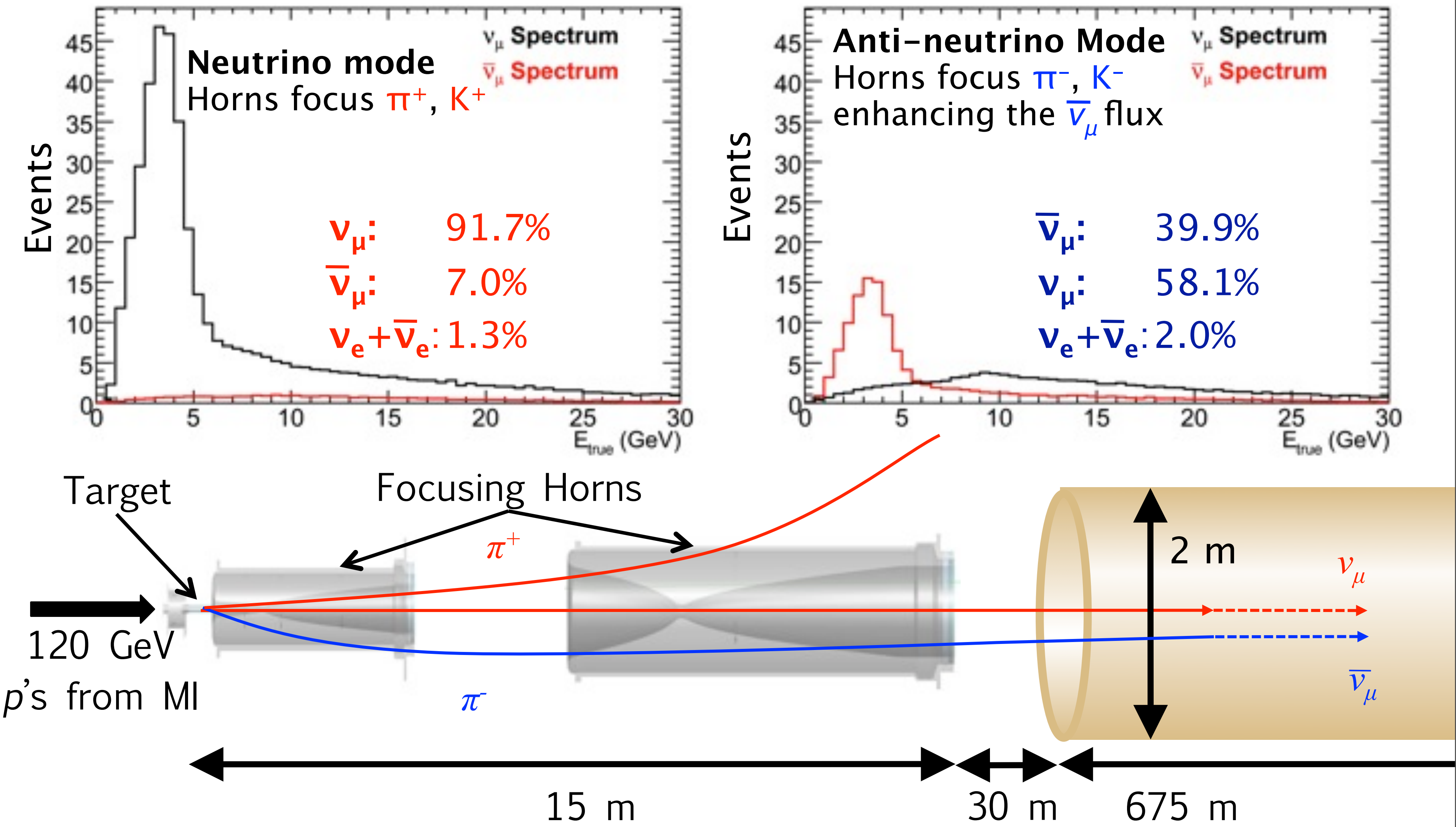
Pure decoherence‡ disfavoured at > **8σ**

† V. Barger et al.,PRL 82:2640 (1999) ‡ G.L. Fogli et al., PRD 67:093006 (2003)

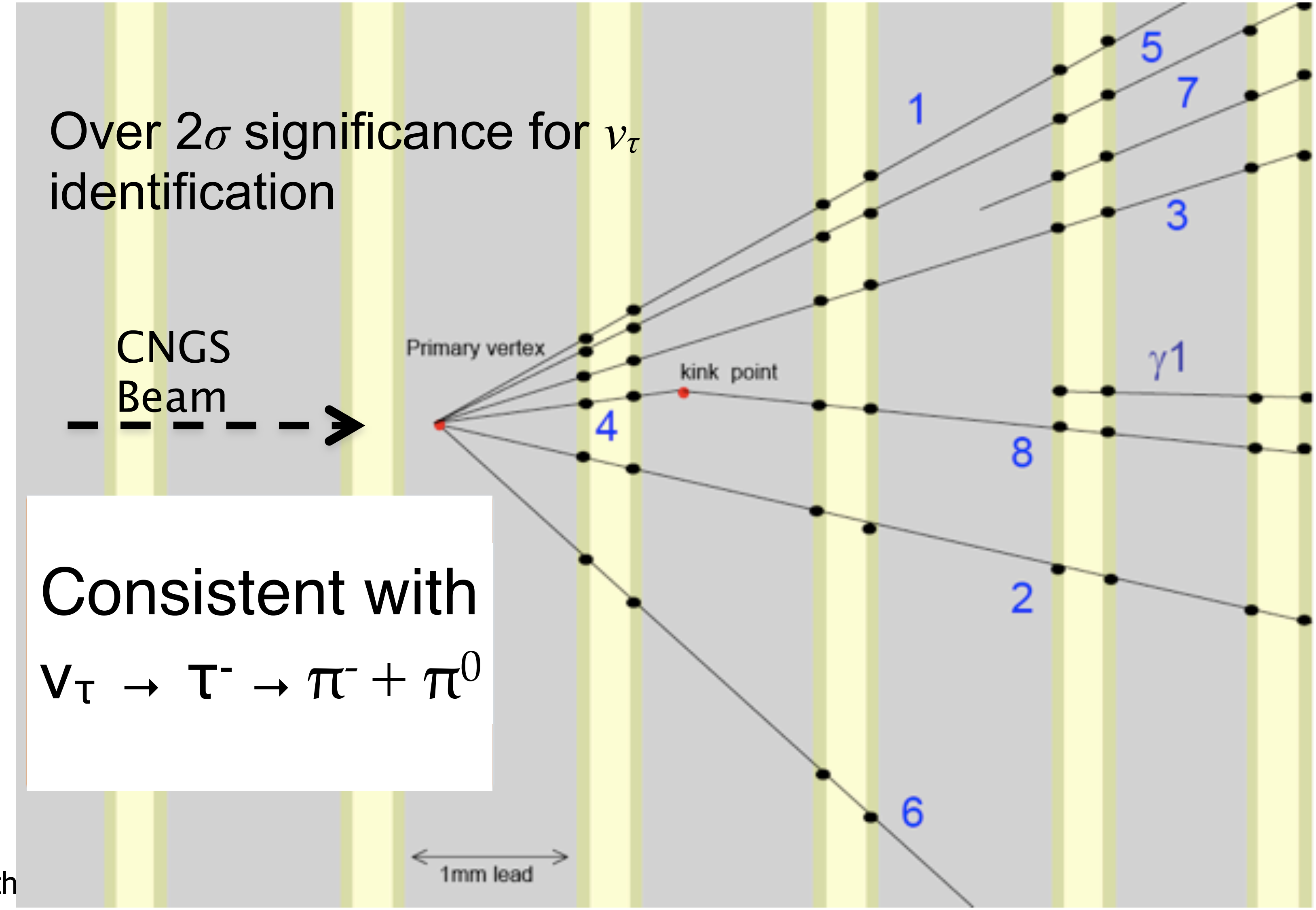
Making a neutrino beam



Making an antineutrino beam



Opera's first tau neutrino



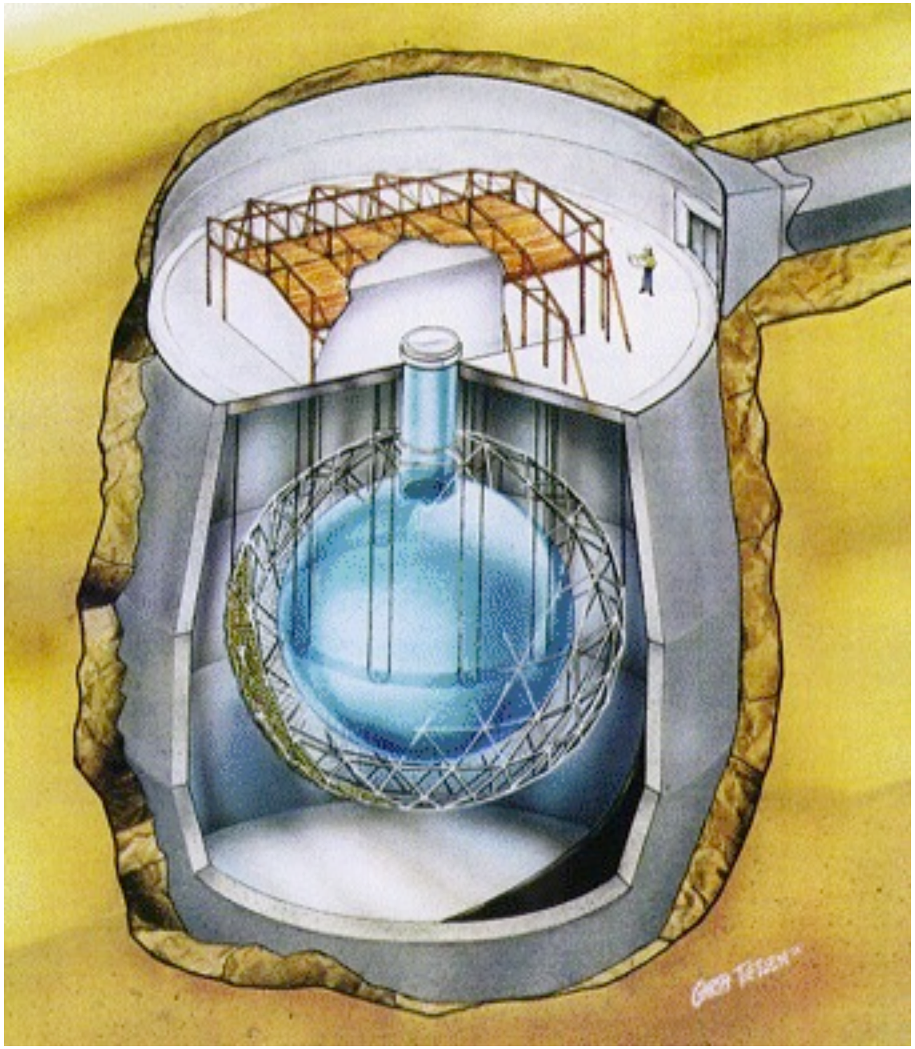
Over 2σ significance for ν_τ identification

Consistent with

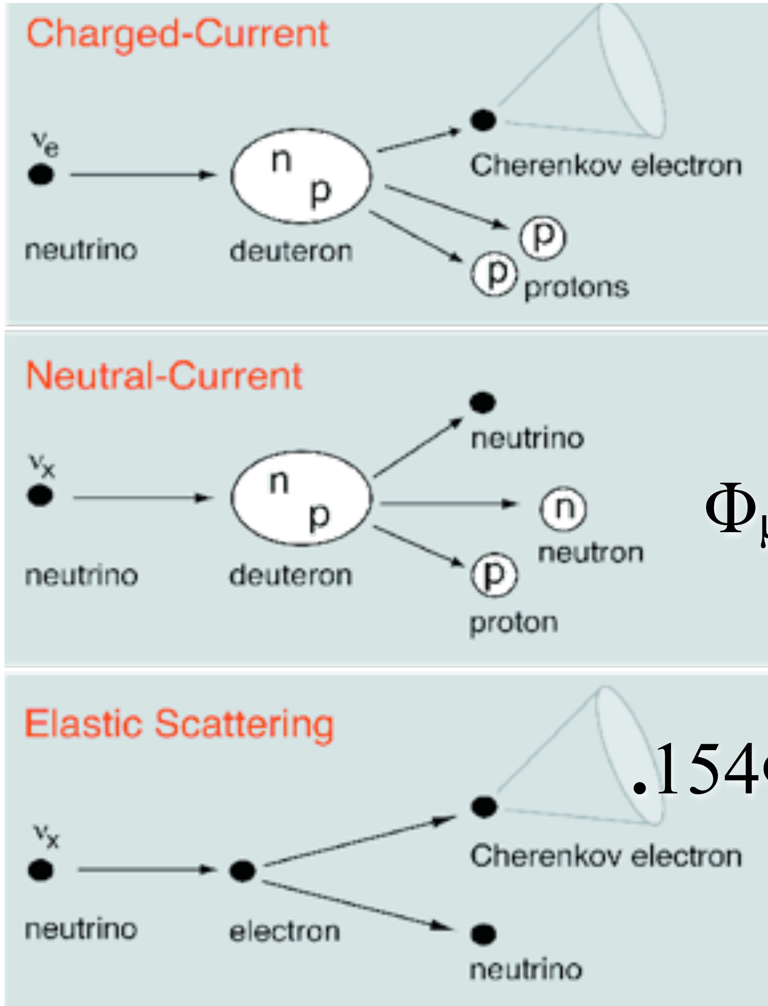
$\nu_\tau \rightarrow \tau^- \rightarrow \pi^- + \pi^0$

26th

SNO



1000 tons of D_2O in a nickel mine
2092 m underground



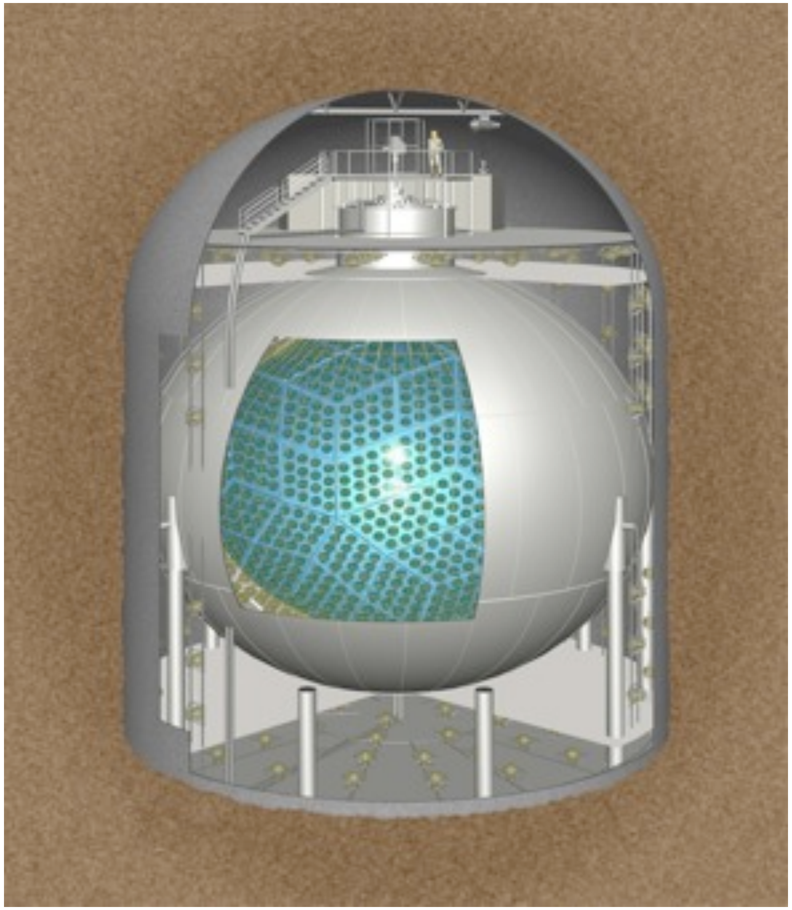
Φ_e

$\Phi_{\mu\tau} + \Phi_e$

$.154\Phi_{\mu\tau}+\Phi_e$

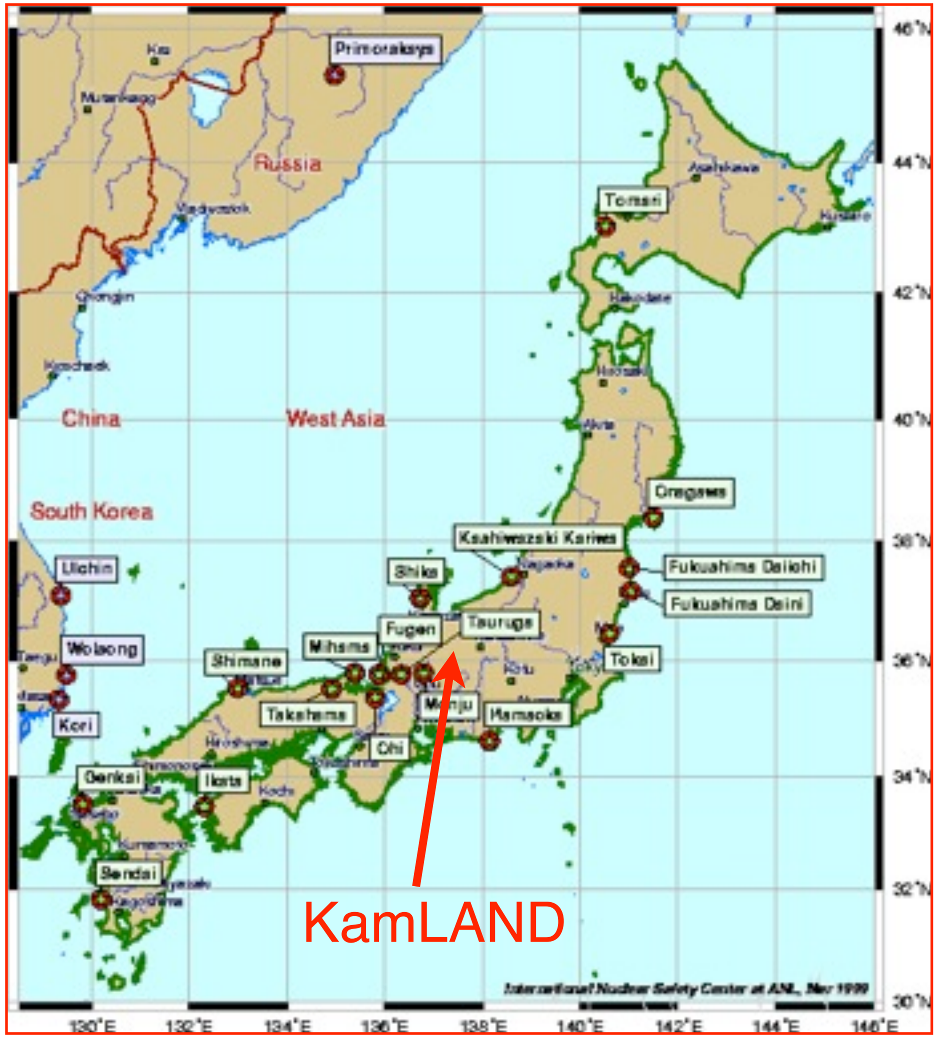
Three measurements (CC, NC, ES)
of two quantities (Φ_e,$\Phi_{\mu\tau}$)

KamLAND



1 kton liquid scintillator
30% photocathode coverage
at 2700 m.w.e. depth

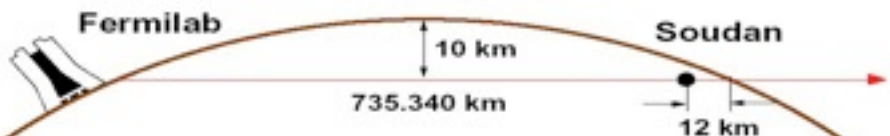
Surrounded by reactors, typically
~180 km away



The MINOS experiment

Produce a beam of muon-type neutrinos

- Fermilab



Near Detector measures the energy spectrum at production

Far Detector again measures the energy spectrum after 735 km

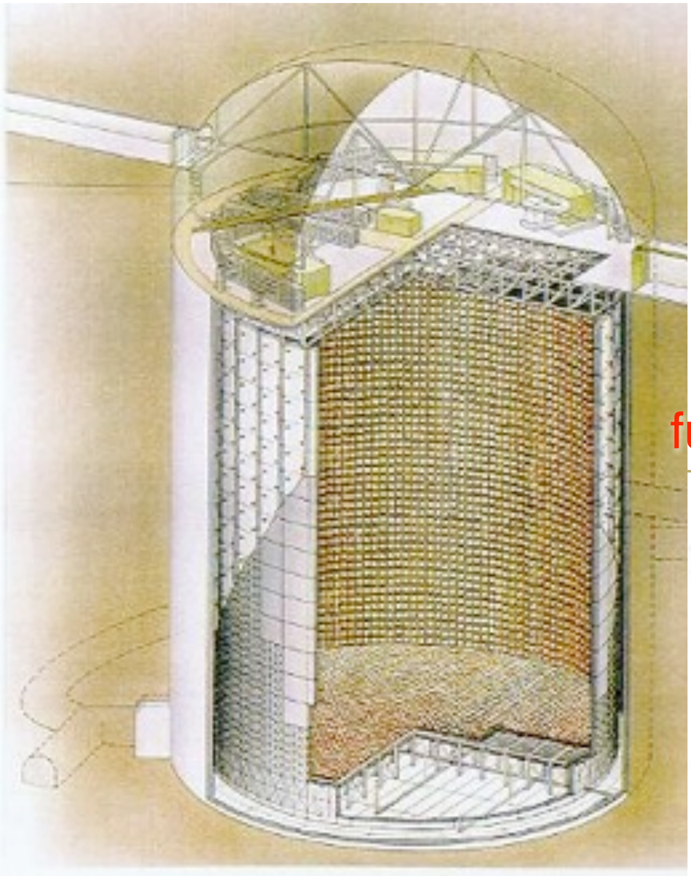
- Sees disappearance or appearance due to neutrino flavour change

Two detectors to mitigate systematics

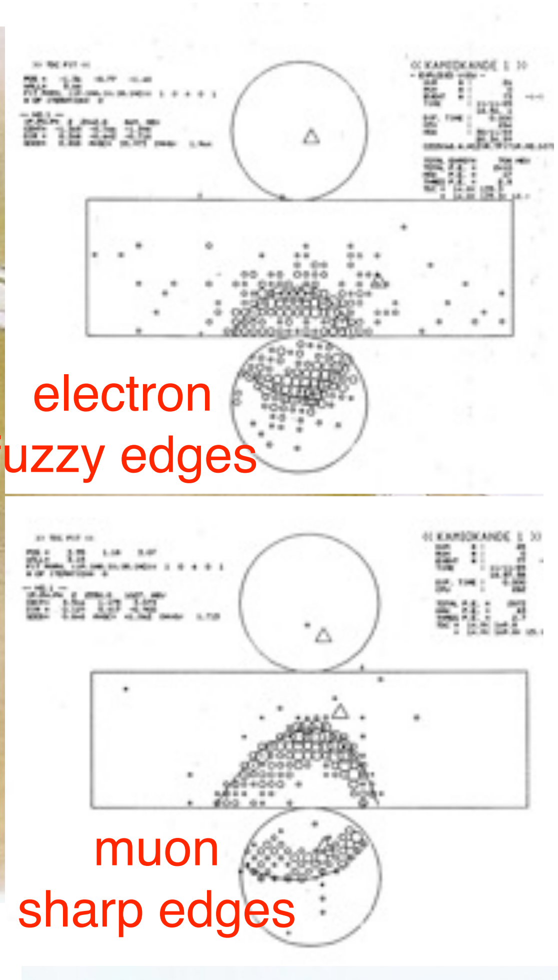
Near Detector
980 tonnes

Far Detector
5,400 tonnes

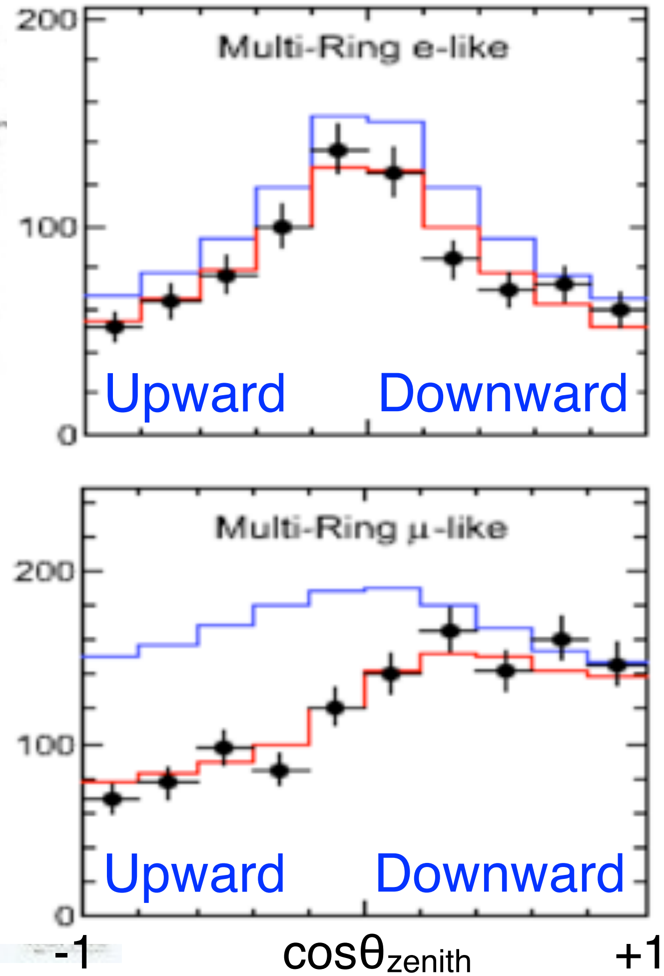
Super-Kamiokande



50 kt of water
42m high, 40 m diam
40% PMT coverage
1000m underground



Example distributions



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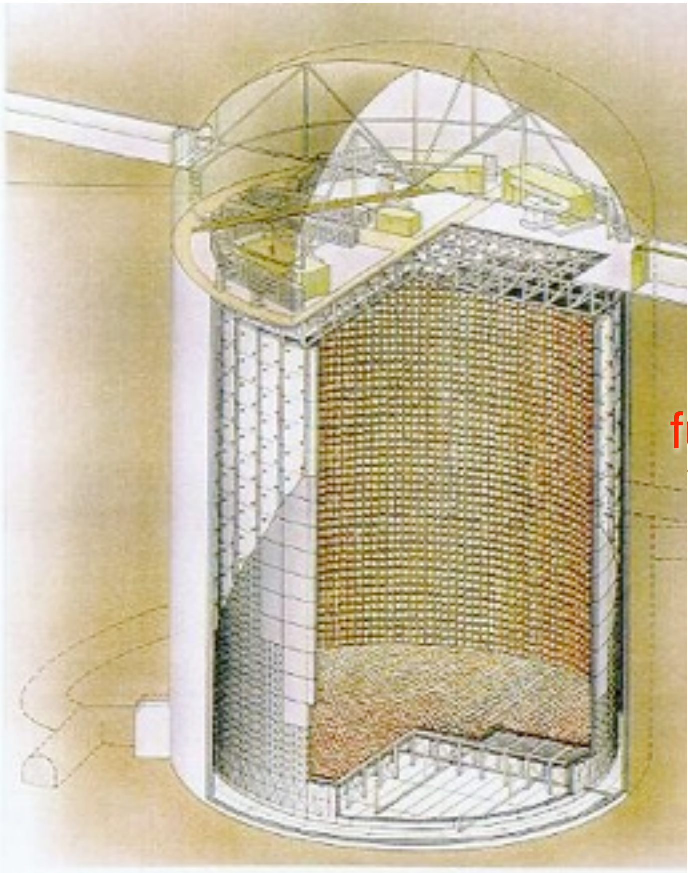

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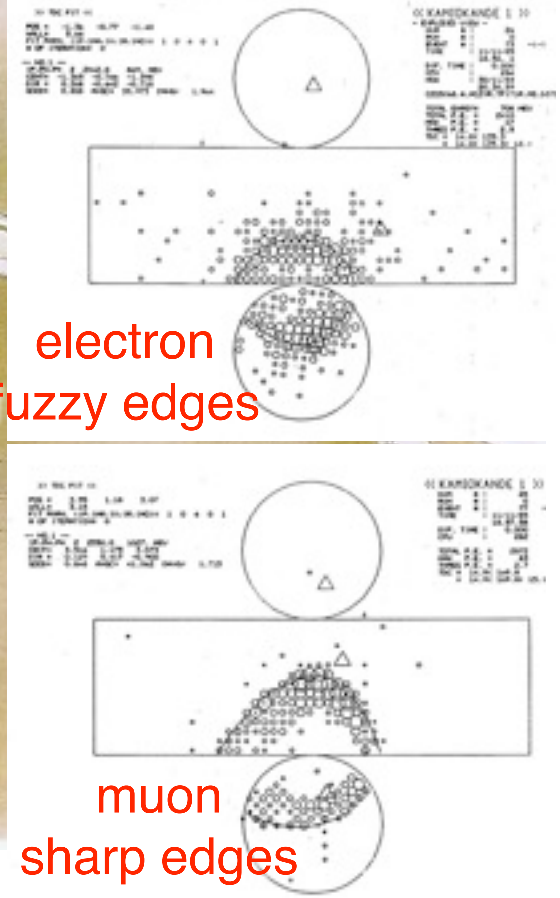

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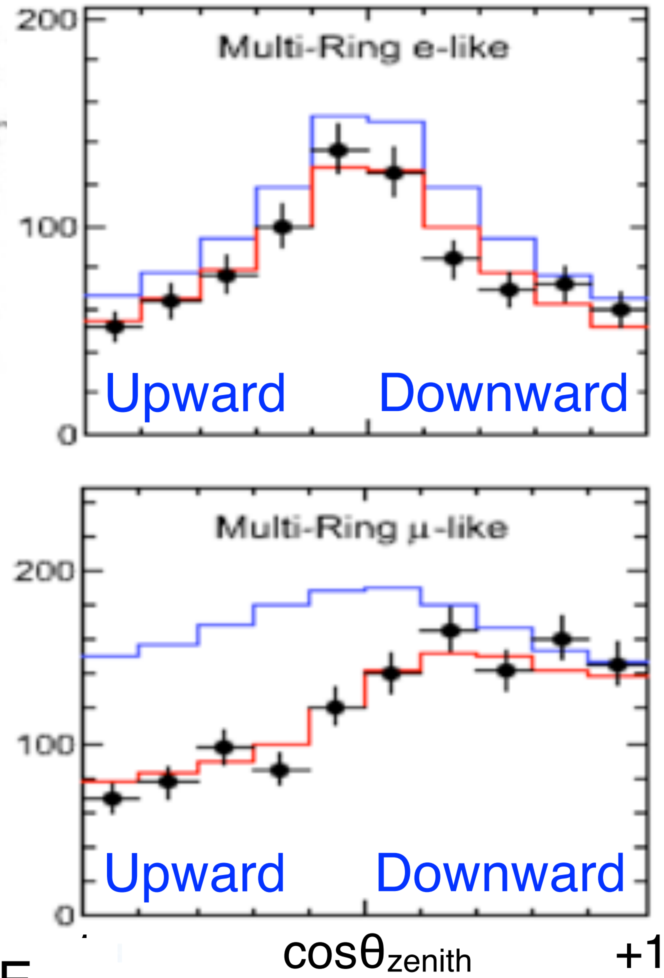

Zenith angle and L/E distributions are used to extract oscillation parameters